

Parsons Power Report No. 9607
DOE Contract Number DE-AC01-94FE62747 / Task 18

Final Report

Assessment of Hot Gas Cleanup Systems for IGCC and PFBC Advanced Power Systems

January 1997

Prepared for:
**The United States Department of Energy
Office of Fossil Energy**

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Table of Acronyms

3M	Minnesota Mining and Manufacturing
ACTF	Asahi Ceramic Tube Filter
AEP	American Electric Power
APF	Advanced Particulate Filter
APFBC	Advanced Pressurized Fluidized Bed Combustion
ATS	Advanced Turbine System
B&W	Babcock and Wilcox
BGL	British Gas/Lurgi
CAAA	Clean Air Act Amendments
CCT	Clean Coal Technology
CFCC	Continuous Fiber Ceramic Composite
CMP	Contract Materials Processing, Inc.
CMRC	Coal Mining Research Center
COE	Cost of Electricity
CPA	Combustion Power Company
CPC	Combustion Power Company
CPFBC	Circulating Pressurized Fluidized Bed Combustion
CRADA	Cooperative Research and Development Announcement
CRE	Coal Research Establishment
CVI	Chemically Vapor Infiltrated
DASH	Dolomite Ash
DOE	Department of Energy
DOE/FE	Department of Energy Office of Fossil Energy
DSRP	Direct Sulfur Recovery Process
E&A	E&A Associates, Inc.
EPA	Environmental Protection Agency
EPACT	Energy Policy Act of 1992
EPRI	Electric Power Research Institute
ESP	Electrostatic Precipitator
FBD	Fluid Bed Desulfurizer
FE	Fossil Energy
FGD	Flue Gas Desulfurization
FWDC	Foster Wheeler Development Corporation
GBF	Granular Bed Filter
GE	General Electric Corporation
HAP	Hazardous Air Pollutant
HGCU	Hot Gas Cleanup
HGD	Hot Gas Desulfurization
HGPF	Hot Gas Particulate Filter
HHV	Higher Heating Value
HTSR	High Temperature Steam Reforming
ICCI	Illinois Clean Coal Institute
IF&P	Industrial Filter and Pump
IGCC	Integrated Gasification Combined Cycle
IGT	Institute of Gas Technology
IHI	Ishikawajima-Harima Heavy Industries Co., Ltd.

KHI	Kawasaki Heavy Industries
KRW	Kellogg-Rust-Westinghouse
LASH	Limestone Ash
LGTI	Louisiana Gasification Technology, Inc.
LLB	Lurgi Lentjes Babcock
LTHGD	Low Temperature Hot Gas Desulfurization
MACT	Maximum Achievable Control Technology
MASB	Multi-Annular Swirl Burner
MCFC	Molten Carbonate Fuel Cell
METC	Morgantown Energy Technology Center
MHI	Mitsubishi
MITI	Ministry of International Trade and Industry
MWK	M. W. Kellogg
NEDO	New Energy and Industrial Technology Development Organization
NRC	National Research Council
NSPS	New Source Performance Standard
ORNL	Oak Ridge National Laboratory
PC	Pulverized Coal
PCD	Particle Control Device
PCFB	Pressurized Circulating Fluidized Bed
PDU	Process Development Unit
PEF	Process Evaluation Facility
PETC	Pittsburgh Energy Technology Center
PFB	Pressurized Fluidized Bed
PFBC	Pressurized Fluidized Bed Combustion
POC	Proof of Concept
PPC	Pyropower Corporation
PSDF	Power Systems Development Facility
R&D	Research and Development
RD&D	Research, Development and Demonstration
RQL	Rich-Quench-Lean
RTI	Research Triangle Institute
SCR	Selective Catalytic Reduction
SCS	Southern Company Services
SiC	Silicon Carbide
SPPC	Sierra Pacific Power Company
SRI	Southern Research Institute
STA	Simultaneous Thermal Analysis
TPC	Total Plant Cost
TPD	Tons Per Day
TRDU	Transport Reactor Development Unit
UARG	Utility Air Regulatory Group
UCI	United Catalysts, Inc.
UNDEERC	University of North Dakota Energy and Environmental Research Center
WCF	Westinghouse Candle Filter
WEC	Westinghouse Electric Corporation

EXECUTIVE SUMMARY

In 1993, the United States Department of Energy (DOE) requested the National Research Council Committee to assess the DOE Coal Program with relation to the provisions of the Energy Policy Act of 1992 (EPACT), and to recommend the emphasis and priorities that DOE should consider in updating its strategic plan for coal. The committee assessed the DOE's Coal Program and concluded that hot gas cleanup is one of the high-priority areas for both Clean Coal Technology (CCT) and Fossil Energy (FE) Coal Research and Development programs. Therefore, the committee recommended in 1994 that "a critical assessment of hot gas cleanup systems for advanced Integrated Gasification Combined Cycle (IGCC) and Pressurized Fluidized Bed Combustion (PFBC) should be undertaken immediately to determine the likely costs and the ability to meet, within the next 3 to 5 years, all requirements for future high-temperature (above 1260 °C [2300 °F]) turbine operation and environmental acceptability". (National Research Council, 1994)

To comply with the recommendation, the Office of Coal Conversion/Fossil Energy requested in 1995 that Parsons Power Group Inc. perform a comprehensive assessment of hot gas cleanup systems under Task 18 of U.S. DOE/FE Contract DE-AC01-94FE62647. The results of this assessment of hot gas cleanup technologies, including particulate collection systems, hot gas desulfurization systems, and trace contaminant removal systems for advanced IGCC and PFBC power plants, are presented in this report. Detailed information on the status of development, impact on cost and performance, technical issues, and need for further development for each system can be found throughout the report. The major findings are presented in **bold** and briefly discussed below.

- 1. The major benefit from hot gas cleanup is seen in higher system efficiencies resulting from retention and utilization of the sensible heat in product gases. Several development programs for hot gas desulfurization systems and hot gas particulate removal systems are under way, as well as control of other pertinent contaminants such as alkali metals and chlorides. Results to date have verified the technical ability to clean hot gases, and longer duration tests will establish the long-term durability record required for commercial acceptance.**

Hot gas cleanup is a high priority for both the Fossil Energy Coal Research & Development and the Clean Coal Technology programs. To date, while hot gas desulfurization systems and hot gas particulate removal systems have successfully completed proof-of-concept tests, neither have demonstrated the long-term performance required for commercial systems. Present designs have accumulated several thousand hours of exposure but have operated for no more than several hundred continuous hours at the required temperatures and pressures.

Research, development and demonstration (RD&D) efforts in hot gas cleanup systems for advanced IGCC and PFBC technology are driven by national objectives related to both economic goals and environmental goals. Clean coal technologies will enable the coal-fired plants of the future to produce low-cost electricity with minimal environmental impact, high efficiency, and high reliability.

- 2. A coordinated program is in place for the development of hot gas cleanup systems and to resolve critical issues. A development plan is being implemented through the demonstration phase for hot gas particulate removal systems, desulfurization systems, and trace contaminant removal systems. This program consists of research and development, proof-of-concept tests, and technology demonstrations.**

The DOE goals for IGCC and PFBC in 2000 and 2010 (DOE, 1993) provide the guidelines for DOE/FE and Morgantown Energy Technology Center (METC) programs in support of hot gas cleanup RD&D as well as support by private industry and institutions. The METC development plan is organized to cover a broad spectrum of RD&D, including fundamental research, filter material and sorbent development, filter system and reactor development, modeling, and system analysis.

- 3. Successful completion of these development plans will demonstrate the ability to meet, within the next 3 to 5 years for IGCC and 4 to 6 years for PFBC, all requirements for future high-temperature turbine operation and environmental acceptability.**

A PFBC CCT demonstration plant has been negotiated with a planned startup date in the year 2000. Outside the U.S., the Karhula, Finland pilot plant and the Wakamatsu PFBC demonstration plant in Japan are testing high temperature filters. With a PFBC CCT project proceeding, a filter demonstration will be in place by the year 2000, which could satisfy the program goals for PFBC. Coupled with the current long-term testing of advanced candle filters at both Karhula and the Power Systems Development Facility (PSDF) in Wilsonville, Alabama, the hot gas cleanup requirements for future high temperature turbine operation for PFBC can be met in the next 4 to 6 years.

For IGCC, three large scale demonstration plants -- Wabash, Tampa Electric Company, and Piñon Pine -- all started up in 1996. All three will utilize candle filters for fuel gas particulate removal, although the Wabash filter operates below 315 °C (600 °F). These filter tests plus the demonstration testing of an integrated hot gas desulfurization system at Piñon Pine and the Tampa Electric Company will keep IGCC within the timeframe of demonstrating all requirements within 3 to 5 years.

- 4. Key tests planned for 1996 and 1997 are critical to the demonstration of both IGCC and PFBC cleanup systems. PFBC tests include filter tests at Karhula, Finland; at the Wilsonville, Alabama PSDF; and at the Wakamatsu PFBC demonstration plant in Japan. IGCC tests include filter tests at the PSDF, slipstream tests of a filter and desulfurization system at the Tampa Electric Company CCT project, and a hot gas cleanup demonstration at the Piñon Pine CCT project.**

In the U.S., pilot plant activities for PFBC were in abeyance when the Tidd CCT demonstration project shut down in 1995. With the startup of the PSDF, PFBC pilot plant testing has resumed in the U.S. The PSDF is a resource for long-term testing and performance assessment of hot gas particulate removal in IGCC and PFBC system environments. For IGCC, testing will be performed at the three large scale demonstration plants that started up in 1996 -- Wabash, Tampa Electric Company, and Piñon Pine.

- 5. Hot gas cleanup systems costs are on the order of 10 to 15 percent of the total plant capital cost for IGCC and 10 percent for PFBC. While significant, this is a much smaller portion than for any other major system. The most critical parameters impacting the cost of electricity include the face velocity for particulate control system, sorbent attrition, and sorbent cost for the desulfurization system.**

The effects of candle filter life and filter element cost on the cost of electricity (COE) of the IGCC plants are an order of magnitude less than the effects of hot gas desulfurization parameters. The candle filter face velocity for the PFBC exit stream is the most important gas cleanup parameter influencing the COE of a PFBC plant. The face velocity of the carbonizer filter has less than half the effect on COE as does the face velocity of the PFBC filter because the carbonizer gas stream is much smaller than the PFBC gas stream. The attrition rate and the unit cost of the desulfurization sorbent have the largest impact on the COE for the IGCC desulfurization system.

- 6. The rapid progress in the development of advanced gas turbines coupled with the successful development of reliable hot gas cleanup systems will assure that the IGCC and PFBC program goals are achieved in the proposed timeframe.**

The gas turbine technology needed to reach the year 2000 goal of 45 percent efficiency (HHV) and 20 percent lower costs for IGCC and PFBC is being developed and is expected to be available. However, the year 2010 goals of 50 percent efficiency (HHV) and 25 percent lower costs for IGCC and PFBC are considerably more ambitious, and will require the advanced gas turbine combined with an economical hot gas cleanup system.

References

National Research Council, Coal: Energy for the Future, Committee on the Strategic Assessment of the U.S. Department of Energy's Coal Program, Board on Energy and Environmental Systems, Commission on Engineering and Technical Systems, December 30, 1994.

DOE, *Clean Coal Technologies: Research, Development, and Demonstration Program Plan*, U.S. Department of Energy, DOE/FE-0284, 1993.

1.0 INTRODUCTION

The National Research Council's (NRC) Committee on the Strategic Assessment of the DOE's Coal Program assessed the future role of DOE in research, development, demonstration, and commercial application programs of coal-based technologies. The Committee was asked to recommend the emphasis that DOE should consider in updating its coal program to respond to the Energy Policy Act of 1992. The Committee recommended that "a critical assessment of hot gas cleanup systems for advanced IGCC and PFBC should be undertaken immediately to determine the likely costs and the ability to meet, within the next 3 to 5 years, all requirements for future high temperature ($>1260^{\circ}\text{C}$ [2300°F]) turbine operation and environmental acceptability." (National Research Council, 1994)

The advanced coal-based IGCC and PFBC power generation systems under development with DOE and commercial funding were divided into three groups by the NRC committee based on projected efficiency:

- Group 1 Approximately 40 percent efficiency - includes PFBC with a low temperature gas turbine; and IGCC with cold gas cleanup, commercially available by 1997-2003.
- Group 2 Approximately 45 percent efficiency - includes PFBC with carbonizer and a commercial gas turbine; and IGCC with hot gas cleanup; by 2002-2005.
- Group 3 50 percent or greater efficiency - includes PFBC with carbonizer and advanced gas turbine; and IGCC with hot gas cleanup and advanced gas turbine; by 2010.

Important features of these systems are summarized in Table 1-1. Information on a state-of-the-art commercial pulverized-coal power plant is also included in the table for comparison. As shown in Table 1-1, a number of advanced IGCC and PFBC systems are projected to achieve efficiencies of 45 to greater than 50 percent using advanced combustion and gasification approaches and high-performance gas turbines. A major objective is to achieve these higher efficiencies at an overall cost of electricity that is 10 to 20 percent lower than that of today's pulverized coal-fired power plants, while also meeting more stringent environmental requirements than present New Source Performance Standards (NSPS).

Table 1-1
Advanced Coal-Based IGCC and PFBC Power Systems

Reserved For Table 1-1

Table 1-1
Advanced Coal-Based IGCC and PFBC Power Systems (concluded)

Still Reserved For Table 1-1

Group 1 power generation systems generally make use of commercially available components and technologies. The NRC Committee expected only limited use of Group 1 PFBC and IGCC plants in the United States. They concluded that the main incentive to continue the domestic demonstration programs was to develop a foundation for the advanced systems.

However, the Committee judged the technologies in Groups 2 and 3 to have greater potential to meet future power generation and associated environmental requirements. All the IGCC and PFBC technologies in these two groups make use of advanced components to achieve higher efficiencies and lower emissions. Major questions of system integration and reliability will need to be addressed, and the first installations would serve as a basis for improvement.

The Committee concluded that the riskiest components for the advanced IGCC and PFBC power plants were the hot gas cleanup systems. Although hot gas cleanup is a component of advanced IGCC power plants, cold gas cleanup could still be used successfully, albeit at a lower efficiency. Since PFBC plants do not have this alternative to hot gas cleanup, the committee also felt that IGCC is a somewhat less risky technology than PFBC.

1.1 Task Objective

The objective of this task is to perform a comprehensive assessment of hot gas cleanup systems for advanced IGCC and PFBC to determine the status of development, to define the cost and performance impact, to identify areas requiring further development, and to estimate timeframes needed to meet the requirements for future high temperature ($>1260^{\circ}\text{C}$ (2300°F)) turbine operation and environmental regulations.

1.2 Technical Approach

The technical approach consisted of three parts: determination of hot gas cleanup status, determination of hot gas cleanup systems cost and performance sensitivities, and identification of the impact of hot gas cleanup systems on program goals and timeframes.

1.2.1 Determination of the Status of Hot Gas Cleanup Technologies.

Hot gas cleanup technologies were divided into three categories: particulate collection systems, hot gas desulfurization systems, and trace contaminant removal systems. Using Parsons Power in-house databases from previous reports and studies, this work focused on recent work, foreign work, and industrial work not necessarily sponsored by the DOE. Information was obtained from literature reviews, personal contact with industry stakeholders, and site visits.

Hot gas cleanup information was documented for each of the three technology areas. Significant tests were summarized, and developmental progress was noted. Sources of information are documented in references at the end of each section.

1.2.2 Determination of Hot Gas Cleanup Systems Cost and Performance Sensitivities

To determine the impact of hot gas cleanup devices on overall system costs and performance, existing IGCC and PFBC baseline plant designs with hot gas cleanup were analyzed. Two IGCC plant designs were chosen which encompass the range of gasifier products and the utilization of desulfurization as either a polisher or as a bulk sulfur remover (Parsons Power, 1995). The first plant design and cost estimate are for the KRW Energy Systems Inc. air-blown gasifier with in-situ desulfurization and a hot gas desulfurizer. The second plant design and cost estimate are for the Destec Energy, Inc. oxygen-blown entrained flow gasifier with a hot gas desulfurizer to remove the bulk of the sulfur. The conceptual plant model for these systems was designed to be readily modified to accommodate changes in hot gas cleanup parameters and equipment.

The PFBC plant model was based on a 535-MW_e Second Generation PFBC design being developed by Foster-Wheeler Development Corporation. The design includes a circulating PFBC and a coal pyrolyzer. The plant design and cost estimates are based on updated work performed in 1992 (Gilbert/Commonwealth, 1993). The base case utilizes limestone sorbent injection in the carbonizer and PFB reactors for sulfur control, and ceramic candle filters operating at 870 °C. (1,600 °F) for particulate control. As with the IGCC study, the flexible PFBC plant model can be modified to accommodate changes in hot gas cleanup parameters and equipment.

Parametric analysis of these designs was used to determine the impact on cost and performance variations in hot gas cleanup technologies and for sensitivity studies.

1.2.3 Identification of the Impact of Hot Gas Cleanup Systems on Program Goals and Timeframes

From the status of hot gas cleanup technologies, development programs promoting the commercialization of hot gas cleanup technology were identified. Test results, technology status, and planned activities were identified for each applicable program. Concurrently, areas of hot gas cleanup technology requiring further development were identified, and the ability to meet the timeframe for specific program goals was assessed. The impact of hot gas cleanup relative to program goals was determined from test results and cost/benefits leading to assessments of the developmental timeframes.

1.3 Report Organization

Chapter 2, for background, gives an overview of development programs for hot gas cleanup systems, IGCC power systems, and PFBC power systems. Chapter 3 presents the status of the technology for particulate control systems, Chapter 4 presents the status of the technology for hot gas desulfurization systems, and Chapter 5 presents the status of the technology for trace contaminant removal systems. Chapter 6 assesses the impact of hot gas cleanup on cost and performance for advanced power systems, and Chapter 7 discusses the impact of hot gas cleanup systems on program goals and timeframes. Chapter 8 presents the findings and conclusions.

1.4 References

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2.0 BACKGROUND

The hot gas cleanup and trace contaminant control programs focus on developing and commercializing gas cleanup subsystems that will be used in PFBC and IGCC power plants.

- The primary activity is the construction of a multi-use test facility in Wilsonville, Alabama. The Power Systems Development Facility (PSDF), started up in 1996, will provide long-term performance testing of up to three different hot gas particulate removal devices simultaneously.
- A Process Development Unit (PDU) at METC, fueled by a syngas generator, will test an advanced 18-inch-diameter fluidized bed reactor and a 6-inch-diameter transport reactor for hot gas desulfurization processes.
- Additional activities include the development and testing of advanced concepts for removing particulates from hot fuel gas, development of new processes and sorbents for hot gas desulfurization, and measurement/control of air toxic species.

2.1 Overview of Hot Gas Cleanup Systems

Current IGCC systems remove particulates by condensing or quenching the raw fuel gas with water (wet scrubbing). Present PFBC designs employ cyclone (inertial) separators upstream of the gas turbine in conjunction with an electrostatic precipitator (ESP) or fabric filter downstream of the gas turbine. Advanced IGCC and PFBC systems will employ rigid, porous (typically ceramic) barrier filters that operate at high temperature, 480 °C to 980 °C (900 °F to 1800 °F), and pressure.

For PFBC systems, the SO₂ reacts with a sorbent injected directly into the fluid bed. This approach is also being examined as an option for IGCC systems employing fluidized bed gasifiers. Gasification-based power systems, including the advanced PFBC system's carbonizer, convert sulfur to hydrogen sulfide (H₂S) rather than SO₂. Current IGCC systems employ cold gas cleanup to remove H₂S with commercial low temperature absorption systems. Advanced IGCC systems are being designed to remove H₂S using an absorption-regeneration system at high temperatures, absorption up to 583 °C(1000 °F) and regeneration up to 705 °C(1300 °F), to improve system efficiency. SO₂, produced from the very low levels of H₂S remaining in the gas stream, results in minimal emissions when the fuel gas is burned to generate electricity.

In gasification-based systems, nitrogen in the fuel gas stream typically occurs as ammonia, which is converted to NO_x upon combustion in the gas turbine. Cold gas cleanup systems remove most of the ammonia prior to combustion, thus lowering potential NO_x emissions, while current hot gas systems do not. In the latter case, post-combustion controls could be required to meet applicable emissions standards.

2.1.1 State of the Art

For PFBC systems, the current technology for sulfur removal employs either a bubbling or a circulating PFBC designed to achieve SO_2 removal efficiencies of 95 percent or more. Scale-up and demonstration of this capability is planned under the DOE Clean Coal Technology (CCT) program. The goal is to achieve SO_2 reductions comparable to modern flue gas desulfurization systems at reagent stoichiometries low enough to permit economical operation with minimum solid waste. Tidd demonstrated a 95 percent sulfur removal at a calcium to sulfur molar ratio of less than 1.5. (Tidd, 1995)

Hot gas desulfurization systems that achieve over 99 percent sulfur removal from gasifier fuel gas streams also are scheduled for demonstrations in conjunction with several IGCC CCT projects. To date, hot gas (480°C to 700°C (900°F to 1300°F)) desulfurization systems employing regenerable metal oxides such as zinc ferrite and zinc titanate have been shown to be feasible, but larger scale and longer duration demonstrations would be needed for commercial acceptance. Continued work on improved sorbents and reactor designs is in progress. System studies for IGCC systems using advanced fluidized bed gasifiers also suggest that the combination of hot gas desulfurization plus in-bed desulfurization in the gasifier using limestone could be beneficial.

Hot gas particulate removal systems for PFBC and IGCC are also under development. These devices can be viewed as integral components of the power generation system, rather than as environmental control technologies, since they serve the critical function of removing particles and alkali metals from the fuel gas to protect the gas turbine from erosion and corrosion. For current and advanced turbine designs, the cleanup requirements needed to protect the turbine from particle-induced damage exceed the current requirements for environmental protection. The most promising systems to date have employed barrier filters.

The major barrier to commercialization, however, has been the lack of long -term continuous operation. Current candle filter designs have accumulated several thousand hours of exposure but have operated for no more than several hundred continuous hours at the required temperatures

(760 °C to 870 °C(1400 °F to 1600 °F)) (National Research Council, 1994). Improved designs, as well as testing in the reducing gas environment of IGCC systems, are planned as part of the CCT demonstration projects.

2.1.2 Current Programs

Currently, the DOE R&D emphasis is placed upon the use of rigid, ceramic filter type devices for particulate removal. Ceramic filters in the form of candle, cross-flow and other configurations have been tested at various industry user facilities, with the most notable one being the AEP's Tidd PFBC demonstration plant in Brilliant, Ohio. Additional tests are being planned at the DOE Power Systems Development Facility (PSDF) in Wilsonville, Alabama, at the Karhula, Finland CPFBC pilot plant and also within a number of Clean Coal Technology projects. Advanced materials are actively being pursued and tested by manufacturers like 3M, Dupont, Pall Vitropore, Coors, and Schumacher. Also, a granular bed filter is being developed by CPC to be tested at the PSDF.

DOE/METC is pursuing the development of hot gas desulfurization systems for application to advanced IGCC and IGFC power plants. Zinc ferrite, zinc titanate, zinc oxide based and Z-Sorb III, a proprietary sorbent developed by Phillips Petroleum Company, have been extensively tested both in the bench-scale units by many research organizations and in a pilot-plant scale by General Electric Corporate Research and Development at Schenectady, New York. These sorbents have been tested in the bench-scale units using the fixed bed, moving bed, fluidized bed, and transport reactors. The sorbents have also been tested by GE in the pilot plant using the moving-bed reactors. Moving-bed and transport reactors will be demonstrated under the CCT Program.

2.2 Overview of Advanced IGCC Power Systems

Components of IGCC technology have been under development since the mid-seventies, and several competing coal gasification processes now have successful commercial-scale operating records. These include the Texaco, Shell, and Destec entrained-flow processes, and the Lurgi moving bed process. Other gasification processes have been successfully tested at pilot scale and are ready for scale-up to commercial size. Pilot-scale processes include the Prenflo entrained flow, the British Gas/Lurgi (BGL) moving bed, and the KRW and the High-Temperature Winkler fluidized bed processes.

The IGCC concept was first successfully demonstrated at the 100 MW_e scale at Southern California Edison's Cool Water station in Daggett, California from 1984 to 1989 using the Texaco entrained-flow coal gasification process. Destec is currently operating a 160 MW_e IGCC plant in Plaquemine, Louisiana, using a two-stage, entrained-flow coal gasification process. In Buggenum, Netherlands, SEP (the joint authority for electricity production) has begun operation of a 250 MW_e IGCC plant based on the Shell entrained-flow coal gasification process.

DOE is currently co-funding three major IGCC projects in the United States under the CCT program. These projects include Wabash River utilizing the Destec two-stage oxygen-blown entrained-flow gasifier, Tampa Electric Company utilizing a Texaco oxygen-blown entrained-flow gasifier, and Piñon Pine utilizing a KRW air-blown fluidized bed gasifier. These projects will use advanced (1260 °C (2300 °F)) firing-temperature combustion turbines. Piñon Pine will also demonstrate the first full-scale hot gas cleanup train to be utilized in IGCC.

DOE's program goals for IGCC systems developed by 2000 and for systems developed by 2010 are summarized in Table 2-1 (DOE, 1993). Efficiency, emissions, and cost goals are set for each time period. First generation IGCC power systems are presently at the commercialization stage, and are being demonstrated with design improvements in the CCT program. The completion of the CCT programs in five or six years will provide the data and experience for subsequent commercial IGCC plants to be deployed beyond the year 2000.

Table 2-1
DOE's Program Goals for Integrated Gasification-Based Systems
(DOE, 1993)

Technology Goals		Integrated Gasification Combined Cycle by the Year 2000 ^a	Integrated Gasification Combined Cycle by the Year 2010
Net efficiency (HHV)		45%	>50%
Emissions,	SO ₂	1/10 of NSPS	1/10 of NSPS
	NO _x	1/10 of NSPS	1/10 of NSPS
	particulates	1/10 of NSPS	1/10 of NSPS
Air toxics emissions relative to 1990 Clean Air Act Amendments		Meet	Meet
Solid wastes		Minimization/reuse	Minimization/reuse
Capital cost (1990 \$)		\$1,200/kW	\$1,050/kW
Electricity cost compared to current pulverized coal		20 percent lower	25 percent lower
Commercial completion milestones		Demonstration 2001	Demonstration 2004
Development status		Under development	Development initiated

^aIntegrated gasification combined cycle power systems at 40 percent efficiency are presently at the commercialization stage, and are being demonstrated with design improvements in the CCT program.

2.3 Overview of Advanced PFBC Power Systems

Development of PFBC has been under way since 1969, when the British Coal Utilization Research Association began operation of a PFBC test unit at Leatherhead, England. A significant portion of the test work conducted there over the next 15 years was supported by the U.S. Environmental Protection Agency (EPA), DOE, and the U.S. private sector. In the early 1980s a number of other PFBC test and pilot facilities were constructed in both the United States and Europe. Under the auspices of the International Energy Agency, the U.S. DOE, the United Kingdom, and the Federal Republic of Germany constructed an 85 MW_{th} PFBC unit that was placed in service in 1980 in Grimethorpe, U.K. Early cooperation between the American Electric Power Service Company and

ASEA STAL (now ASEA Brown Boveri with its subsidiary ABB Carbon) led, in 1982, to the construction of a 15 MW_{th} PFBC Component Test Facility now located in Finspong, Sweden (Miller and others, 1982).

In the United States, the Foster Wheeler Development Corporation, under the sponsorship of the DOE, constructed and operated an advanced PFBC proof-of-concept facility in Livingston, New Jersey. The plant was operated in both a carbonizing and combustion mode to validate commercial plant performance predictions.

A fully integrated PFBC system with a carbonizer is also scheduled to be tested at the 4 MW_e level at the PSDF under construction in Wilsonville, Alabama, sponsored by DOE, Southern Company Services, Foster Wheeler Development Corporation, and EPRI. This PFBC testing will evaluate the integration of all of the components in the PFBC system, with emphasis on the integration of hot gas cleanup ceramic filters and gas turbines (McClung and others, 1995). This test facility will provide design input for the planned CCT demonstration unit described below.

Presently, PFBC technology is in the early stages of commercialization. Five PFBC units of less than 80 MW_e, two in Sweden, one in Spain, one in the United States and one in Japan, have been placed in operation over the last five years. The two PFBC units at the Värtan plant in Stockholm have operated since 1991. The Spanish state-owned utility ENDESA has also operated a PFBC unit since 1991. The U.S. unit was the 70 MW_e Tidd CCT project, which has been completed. The Japanese 71-MW_e unit is in initial operation. These units are all of the bubbling bed variety with efficiencies in the 40 percent range.

In addition to the Tidd project in the United States, the DOE CCT program is also sponsoring two other PFBC projects. One is a 150 MW_e circulating PFBC project, which was to have been in operation by mid-1997. The schedule was revised due to a merger of one of the participants. This circulating PFBC unit is a system with an efficiency in the 40 percent range but includes a hot gas particulate removal device.

The second CCT PFBC project is an advanced system with an efficiency in the 45 percent range. This PFBC system will involve partial gasification of the coal, with the resulting fuel gas going to a topping combustor along with cleaned gases from a circulation unit that will receive char from the gasifier. Electricity is generated by the topping cycle, and by a steam cycle coupled to the PFBC unit. An advanced system for hot gas cleanup will also be used in the demonstration. Negotiations have been completed for the combination of these two CCT projects into one with the

circulating PFBC followed by the installation of a carbonizer for the advanced PFBC demonstration.

The current PFBC program is aimed at developing advanced systems for electric power generation with both shorter and longer term goals for efficiency, emissions, and costs. The PFBC program goals are summarized in Table 2-2 (DOE, 1993).

Table 2-2
DOE's Program Goals for Pressurized Fluidized Bed Combustion Systems
(DOE, 1993)

Technology Goals		Pressurized Fluidized Bed Combustion by 2000 ^a	Pressurized Fluidized Bed Combustion by 2010
Net efficiency (HHV)		42%	50%
Emissions,	SO ₂	1/5 of NSPS	1/10 of NSPS
	NO _x	1/5 of NSPS	1/10 of NSPS
	particulates	1/5 of NSPS	1/10 of NSPS
Air toxics emissions relative to 1990 Clean Air Act Amendments		Meet	Meet
Solid wastes		Minimization/reuse	Minimization/reuse
Capital cost (1990 \$)		\$1,100/kW	\$1,000/kW
Electricity cost compared to current pulverized coal		20 percent lower	25 percent lower
Commercial completion milestones		Demonstration 2000	Demonstration 2003
Development status		Systems development, integration and testing ongoing	Development initiated in the nineties

^aPressurized fluidized bed combustion power systems are at the 70 to 80 MW_e demonstration phase with a 350 MW_e unit planned to start up in Japan by 1998.

2.4 References

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3.0 STATUS OF THE TECHNOLOGY- PARTICULATE COLLECTION SYSTEMS

The major benefits of utilizing hot gas particulate removal include the capability for obtaining higher system efficiencies, complying with environmental requirements, and protecting advanced gas turbines from erosive particles. The development of advanced power systems is aimed toward the use of particulate collection temperatures of 370°C to 595°C (700°F to 1100°F) for IGCC and 760°C to 870°C (1400°F to 1600°F) for PFBC.

Commercially available cold gas cleanup technology could be used for IGCC applications, although it would incur higher costs and an efficiency penalty. In contrast, advanced PFBC systems require hot gas filtration since cold gas cleanup is not a practical option. Thus, hot gas particulate removal is a high-priority for both the Clean Coal Technology (CCT) and the Fossil Energy coal R&D programs.

The U.S. involvement with high-temperature, high-pressure particulate removal started in 1978, primarily for PFBC. At least 10 devices were tested at a bench scale under simulated PFBC conditions. In 1982 two devices, a ceramic felt bag filter and an ESP, were installed at the Curtiss-Wright PFBC pilot plant and tested at actual PFBC conditions. In 1986 a granular bed filter, a redesigned ESP, and a ceramic cross flow filter were tested at the New York University PFBC pilot plant.

In Europe, silicon carbide candles were being tested in England at Grimethorpe's PFBC and at other test facilities in Germany and Finland. By 1989, the candle filter appeared to have the best chance for success in both PFBC and IGCC environments. A demonstration-scale test of a candle filter was done at the Tidd PFBC plant and results of the final series of tests were positive, although long term testing above 815°C (1500°F) is still needed. Other devices such as cross flow filters, ceramic tube filters, and granular bed filters continue to be developed but will need much more testing at pilot and demonstration plant scale before acceptance is attained.

Presently, a coordinated program is in place to commercialize hot gas particulate collection technology. This program includes Research & Development, slipstream testing, pilot plant testing, and CCT demonstration plants. This section presents the status of particulate collection at high temperature and pressure for both IGCC and PFBC. The information was obtained from published articles, contacts with vendors, and discussions with personnel at test facilities. A brief discussion on the fundamental mechanisms of particle separation is given, followed by an identification of filter developers. Filter testing status is summarized and the technical issues remaining are discussed.

3.1 Basis of Gas Separation at High Temperature and Pressure

3.1.1 Fundamental Mechanisms of Particle Separation

The fundamentals of particulate removal from gas streams have been studied and equations have been formulated to predict filter performance (Gilbert/Commonwealth, 1993). Above 500°C (930°F) there is less information; however, theoretically, the filters should perform similarly at high temperatures and pressures since they employ the same particle capture mechanisms. The capture mechanisms involved are:

- Interception
- Diffusion
- Inertial impaction
- Gravitational settling
- Electrical migration (for ESPs)

The most important physical characteristics of the particle relating to these capture mechanisms are density and diameter. Removing particulates from a high-temperature, high-pressure gas stream for physical characterization is difficult, but techniques have been developed to collect representative, isokinetic samples from both gasifier and PFBC environments. In situ analysis is being developed using laser spark spectroscopy and Fourier transform infrared spectroscopy, providing another analysis technique. Real-time measurements will provide histories of alkali and particulate concentrations. However, it must be emphasized that many fundamental process parameters are not yet commonly available nor easily estimated by theoretical means.

There are two possible complications that can affect particulate collection for which no analytical mechanism exists: re-entrainment during blowback of barrier filters or the rolling of media in granular bed filters; and penetration of particles due to bypassing, cracks or construction defects.

After the particles are collected on barrier filters (or on granules) they must be blown off and separated. In order for this to occur, the blowback pressure must be sufficient to stop the forward filtration of the dirty gas and exceed the cohesive force among the particles and the adhesive force between the particle or cake and the filter medium. This force is called "separation stress" and it is a complex function of material, temperature, pressure and the manner in which the particle is deposited. A fair amount of modeling and research has been done concerning separation of particles from barrier filters (Chen and others, 1994). The purpose of this modeling work was to find ways to reduce harmful effects of blowback on the ceramic filters.

3.1.2 Pressure Drop Considerations

The total pressure drop for a barrier filter consists of the clean element pressure drop including the clean gas duct work, which is a function of gas flow, density, and viscosity; the residue pressure drop, which is a result of "conditioning" the filter; and the filter cake pressure drop, which is a function of the cake permeability as it builds up on the filter element. For a gasifier or PFBC the filter pressure drop affects equipment size (capital cost), operating efficiency and maintenance costs. However, because of the high operating pressure of these systems it is not a significant factor. It is more important that the barrier filter operates continuously and reliably. Typically at PFBC conditions candle filters operate with pressure drops between 1 and 6 psig depending on cake adhesivity.

Filter cake pressure drop can be predicted if data such as particle size distribution, loading and cake porosity are available. A serious problem is that there is not much data for PFBC and gasifier particles and filter cakes that can be used in these theoretical equations. This issue is being addressed however by both DOE and industry. Determining filter cake pressure drop will allow calculations of blowback cleaning requirements and cake cleaning efficiency. This information can be used to optimize the design and operation of blowback systems. DOE/METC is currently pursuing several methods to understand filter cake strength and back-pulse cleaning. .

3.1.3 Candle Filter Design Considerations

Candle filters are typically suspended from a tube sheet, which may be made from high-temperature metal, or from ceramic in the case of the lighter weight ceramic filters. Each tubesheet holds an array of individual candles, and tubesheets may be grouped horizontally and vertically. Tubesheets may be solid, or hollow for water cooling. The filters are closed or sealed on one end and flanged on the other end for mounting on the tube sheet. The candles are typically hung from a horizontal tubesheet, but one recent design supports them from the bottom. Various methods are used to secure the candles to the tubesheet, including weights, clamps and springs. Care must be used in making this connection, since there is a pressure differential across the connection which may cause leaks across the tube to tubesheet seal, as well as the effects of absolute and differential expansion, and thermal and mechanical shock during cleaning.

Candles are cleaned by sending a surge of air or inert gas backwards through the candle wall. Experience to date has shown that a "pulse" system, wherein a short, high-pressure pulse of gas is injected on the clean side of the candle, apparently works better than a back flow system, where a lower pressure, longer back flow of gas is used. Systems where isolation of elements for cleaning is used require extra filter elements, increasing the filter system costs. Also, the gas used for pulse cleaning is usually much cooler than the filter element, and can cause thermal stress on the elements

A new, clean filter has an intrinsic pressure drop that is a function of face velocity. As the filter is subjected to normal use and cleaning cycles, the pressure drop across the filter will build up until it reaches an equilibrium, which will normally be around twice the initial clean pressure drop at equal face velocity. The value of the equilibrium pressure drop is important to the design of the filter as well as the rest of the plant, and should be determined by testing of actual coal during plant design if possible.

Pressure drop across the candle filter wall can be controlled in several different ways. By varying the wall thickness, the pressure will vary substantially, assuming other factors are held constant. However, wall thickness may be dictated by strength requirements and may not be variable. Porosity can also be varied. Some filters are manufactured with more than one layer, each with a different pore size, the outer layer or skin with smaller pores to prevent small particles from entering the pores.

3.1.4 Anticipated Performance of Barrier Filters

For both gasifier and PFBC systems the purpose of the particulate collection device is to protect the turbine and to meet environmental emission standards. Although turbine manufacturers have proposed different inlet standards, in general, the following inlet conditions are expected:

Particle loading	< 29 ppmw (Required to meet NSPS)
Particle size	< 1 ppmw of >10 micron
Particle size	< 8 ppmw of > 5 micron

Results from tests of candle filters, cross flow filters and other ceramic barrier filters have shown that the above inlet requirements can easily be achieved when the filters are functioning as designed and are intact. It is important in any system design using ceramic filters that fail safe designs be incorporated or on-line failure protection devices are installed to detect process problems or filter breakage so that the turbine is protected. Recent filter system designs have incorporated fail safe mechanisms.

3.2 Particulate Collection Device Developers

High-temperature particulate collection has been attempted using several types of equipment, ranging from new devices developed specifically for the service, such as candle filters to modified traditional devices, such as upgraded electrostatic precipitators. Lately, work has centered on the development of candle filters, although there is still interest in other devices such as granular bed filters and cross flow filters. This section reviews the different devices that have been proposed for hot gas particulate removal and identifies the system and component developers of each. Table 3-1 is an overview of developers and products.

Table 3-1
Overview of Particulate Control Device Developers

	Ceramic Candle System	Ceramic Candle Element	Ceramic Fiber Candle	Ceramic Tube	Ceramic Cross- flow	Sintered Metal	Granular Bed System	Cross Flow System
Westinghouse	X		X				X	
Schumacher	X	X						
Pall	X					X		
IF&P	X		X					
LLB	X							
Refractron ¹		X						
Coors		X			X			
3M			X					
B&W			X	X				
Lanxide			X					
Textron			X					
BFW			X					
Asahi				X				
Blasch					X			
CeraFilter					X			X
Combustion Power							X	

1. Refractron is the sole supplier to Pall

3.2.1 Ceramic Candle Filter System Developers

The candle filter has the most extensive testing of any high-pressure, high-temperature particulate filtration device. Ceramic candle filters are commercially available for moderate temperature and pressure applications and several suppliers will offer commercial and advanced systems. Not all of the system suppliers manufacture the filter elements used in their filter systems and several manufacturers furnish only the filter elements. Following is a brief introduction to the major suppliers of candle filter systems for high temperature and pressure service.

- Westinghouse has the most experience in designing candle filter systems for gasifiers and PFBCs. They do not manufacture the filter element but procure them from outside sources. Their patented design consists of clusters of candles, arranged in plenums with a single blowback tube for each plenum. The vessel tested at Tidd had three clusters with three tiers each containing over 350 candles. A similar size vessel using a maximum of 273 candles and a fail safe device will be tested at Wilsonville on the PFBC combustor.

Westinghouse is providing the ceramic candle filters for the 95-MW_e Piñon Pine IGCC project. Westinghouse also had agreements with both Pyropower and Foster Wheeler to design and supply filters for their respective PFBC Clean Coal Demonstration Plants. These projects were combined into a single plant to be located in Lakeland, Florida. Westinghouse will provide the filter system with guarantees to be negotiated for the combined project.

Westinghouse is testing advanced clay binder silicon carbide candle filters at Karhula which are capable of operating above 850°C (1560°F), a requirement for PFBC. Westinghouse designed the filter vessel internals for the Karhula, Finland circulating pressurized fluidized bed test facility. The Karhula filter is essentially one third of the Tidd scale filter. (Lippert, 1996)

- Schumacher designed a 600 candle filter vessel for the Buggenum gasifier that is reported to be operating successfully. During 3000 hours of testing the strength of the candles did not decrease; however, some candles broke apparently due to mechanical problems. They have also furnished the filter for the Wabash gasifier which they consider to be their "standard" design. Both filters were designed to clean fuel gas at a temperature below 315°C (600°F). Currently attempts are being made to design more efficient packaging arrangements for candles in a vessel. Schumacher does not provide filters in vessels using tiers of candles. Consequently the Buggenum and Wabash design has a single tube sheet. Candles are being sold for operating at 650°C (1200°F) at gasifier conditions and 750°C (1380°F) at PFBC conditions; however, if tests of advanced clay binder candles at Karhula are

successful, the candle operating temperature for PFBC will be raised to 850°C (1560°F). (Seymour, 1996; Durst, 1996; Walsh and others, 1996)

- Pall designed the stainless steel tube filter assembly which was tested at gasifier conditions at Waltz Mills. Tests were successful when sulfur in the gas was at low levels. A 56 candle filter will be tested at the Tampa Electric Company IGCC plant on a slip stream of fuel gas downstream of the hot gas desulfurization system. Sintered metal and perhaps ceramic candles will be tested.

Pall now has a marketing license with Refractron to use their ceramic filter elements for PFBC conditions. In December of 1995 a patent for a high temperature, high pressure filter vessel was issued to Pall incorporating a fail safe design for filter breakage. They are building a small unit to be tested on a combustion plant in a VEAG-led project in Germany. (Seville and others, 1996)

Pall has submitted proposals for filters at IGCC plants in Japan but there are no high temperature filters currently being tested in IGCC plants in Japan. PFBC plant designs in Japan are being considered and Pall may have some involvement. Pall and Refractron are involved in testing the high temperature candle at 850°C (1560°F) with advanced clay binders at Karhula. Their current candle is not guaranteed for above 650°C(1200°F). (Sawyer, 1996)

Pall will test a 56-candle filter at the Tampa Electric Company CCT IGCC demonstration plant. The filter will be located downstream of the desulfurization process with the blowback gas being preheated. Pall has recently received a patent for a high-temperature, high-pressure filter vessel design for any type of filter that uses an inner filter in each candle as a fail safe device. Pall will not recommend a sintered metal filter for service in PFBCs operating above 650°C (1200°F). (Sawyer, 1996)

- Industrial Filter & Pump (IF&P) will supply filter systems for both PFBC and gasifiers using the Fibrosic candle. They have designed a pilot plant filter vessel comprised of a single tube sheet with six plenums each containing 15 candles. This design will be tested at Wilsonville on the M. W. Kellogg transport reactor. The commercial status of the larger vessel is not known but IF&P feels it can be designed for PFBC and gasifier conditions. (Zievers, 1996)
- Lurgi Lentjes Babcock (LLB) Energietechnik GmbH has developed a candle filter system which differs from the other commercially available filters in that the candles are supported from below on a manifold system. The elements are kept under compressive stress by mounting them 'upside down' on the horizontal clean gas header pipes. With this design, filter changes are claimed to be easier and several elevations of filters are possible. A 600 candle vessel with membrane coated silicon carbide ceramic filter elements was tested with success at the Rheinbraun AG-Berrenrath coal gasifier at

temperatures to 350°C (660°F). Testing is now being done at 850°C (1560°F) at the LLB 15-MW_{th} PCFB pilot plant using seven different candle materials in a vessel holding up to 124 candles. LLB's design has been selected for the Puertollano, Spain IGCC plant. Two 900-candle vessels will operate at 230°C (450°F) and 25 bars. The LLB design allows valving off of sections that contain broken candles without need for shutdown of the unit. LLB does not manufacture the filter element but procures them from outside sources. (Ondrey, 1994; LLB).

3.2.2 Ceramic Candle Filter Element Developers

Ceramic monolithic candle filters were the first type of candle filters to be designed, manufactured and tested in the hot gas cleanup program for coal gasification and PFBC gases. The three companies that provided these candle filters were:

- Refractron - Clay Bonded Silicon Carbide: Silicon carbide grains held together with a clay based binder (Pall Corporation currently has a marketing license agreement with Refractron for sales of ceramic candle filters)
- Coors - Alumina Mullite: A monolithic oxide ceramic, made up of mullite, anorthite and alumina.
- Schumacher - Clay Bonded Silicon Carbide: Silicon carbide grains held together with a clay based binder.

Ceramic fiber candle filters have been developed to provide a material that could solve the problems that were experienced with the monolithic type ceramic filters. These materials are tougher than ceramics and do not fail in a brittle manner. It is expected that the composite material will not creep or be degraded by exposure to a hot gas cleanup environment. (Pontius, 1995) The filter suppliers for these materials are:

- 3M CVI Silicon Carbide - Nextel Continuous Fiber Composite: Nextel (aluminosilicate) fibers with CVI silicon carbide coating. A carbon interface coating is used. Chopped fibers bonded with CVI SiC make up the filtration layer which is held in place with an over wrap of CVI coated fibers. This type is being tested at Karhula at PFBC conditions. Second generation candle filters made of 3M CVI-SiC composite have also under gone testing at one of the Westinghouse hot gas filtration systems in Pittsburgh. (Alvin and others, 1995a; Fischer, 1995)
- B&W Continuous Fiber Ceramic Composite: Filament wound alumina based fiber, infiltrated with chopped fibers which form the filtration surface. A program to develop a filament wound alumina based filter with a coating matrix of chopped ceramic fiber (Saffil) has been initiated. Mitsui's

ALMAX alumina fiber and 3M's NEXTEL 610 alumina fiber will be used as the basis for the filters. (Wagner, 1996)

- Dupont Lanxide PRD-66: An oxide ceramic material derived from wound fibers containing alumina, mullite, cordierite and a glass phase. The micro-structure is micro-cracked. A version of this type was tested at Tidd. Second generation candle filters made of Dupont PRD-66 are presently being developed and tested at one of the Westinghouse PFBC hot gas filtration systems in Pittsburgh. (Alvin and others, 1995a; Chambers and Garnier, 1996)
- Dupont Lanxide Silicon Carbide Composite: Silicon carbide fibers coated with CVI silicon carbide. A fiber interface coating is used, which is probably carbon. Chopped fibers make up the filtration surface. Second generation candle filters made of Dupont SiC-SiC are presently under going testing at one of the Westinghouse PFBC hot gas filtration systems in Pittsburgh. (Alvin and others, 1995a)
- Textron Continuous Fiber Ceramic Composite: Filament wound, Textron SCS-6 SiC fiber, nitride bonded silicon carbide composite. SCS-6 fiber surface provides appropriate mechanical properties. Difficulty in maintaining porosity and strength have raised questions concerning the usefulness of this formulation. (DiPietro, 1996)
- Westinghouse/Techniweave/3M: 3-D woven NextelTM (aluminosilicate) fiber infiltrated with mullite using a sol gel process. A program is presently underway to develop and test a fiber architecture and a fabrication process for a Nextel 550 based fiber-reinforced ceramic composite material which may overcome the problems associated with earlier ceramic candle filters. If successful, further funding may be obtained to fabricate and test full size candles in a facility such as Wilsonville. (Lane and others, 1996)
- IF&P Fibrosics: Vacuum formed chopped aluminosilicate fibers, having light weight and low strength. IF&P has developed a light weight modified aluminosilicate material (Fibrosic) that can be used for candles and other parts of the filter structure, such as tubesheets. Since the candles are much lighter than monolithic ceramic candles, the tubesheet can support candles made of Fibrosic but not of the heavier ceramics. IF&P is presently involved in a program to develop a candle filter material that is stronger and can withstand higher thermal shock levels than the presently available aluminosilicate material. Second generation candle filters made of IF&P FibrosicTM are also presently under going testing at one of the Westinghouse PFBC hot gas filtration systems in Pittsburgh, Pennsylvania. (Alvin and others, 1995a)
- BWF America, Inc. - Alumina silicate fiber, or argillaceous earth silicate fiber ceramics. Alumina silicate fiber ceramic filter elements were designed and tested in power plant conditions(i. e. at low

pressure) on three plants at temperatures of 650°C to 920°C (1200°F to 1690°F) for up to 2600 hours. The elements have also been tested on filtering other types of materials with similar results.(Hilligardt, 1995)

3.2.3 Ceramic Tube Filter Developer

The tube filter manufactured by Asahi Glass Co., Japan, is 2 to 3 meters long, 170 mm O.D. and 140 mm in I.D., and is typically made of porous cordierite. The tube elements are butted together to form 20-ft. vertical units, and 9 to 85 of these units can be housed in a pressure vessel. The tube differs from a candle filter in that it requires mounting fixtures on both ends where they are butted together. There are tube sheets at the top and bottom of the butted tubes. Furthermore, in operation, the dirty gas enters at the top then flows downward inside the tube at high velocity. Clean gas exits horizontally and outside the vessel through side outlets. The candle filter, on the other hand, operates with the dirty gas on the outside of the filter. The Asahi tube filters are blown back by a reverse pulse through the clean exit pipes using a venturi effect. A novel feature of the pulse cleaning system is the use of a regenerative wire mesh heat exchanger to heat the pulse cleaning air (and entrained clean gas) prior to its entering the clean gas compartment, the intention being to minimize thermal shock.(Weitzel, 1995)

3.2.4 Ceramic Cross Flow Filter Developers

Ceramic cross flow filters were developed to provide a hot gas cleanup device that could perform the same function as a candle filter, but in a smaller piece of equipment. The filter is made up of layers of porous ceramic laid in strips to create passageways. The gas inlet side strips are laid at 90° to the gas outlet strips so that gas flows have to pass through a ceramic membrane to exit. By arranging the gas passageways in this manner, the utilization of space available is maximized. With the same face velocities, which has been shown to be a reasonable assumption, the Westinghouse cross flow filter has approximately three times and the CeraFilter seven times the surface area per unit volume of a candle filter. Hence a cross flow filter system would be much smaller in size than a candle filter would be for the same duty. (Proceedings, 1992)

- Westinghouse: Composed of alumina/mullite ceramic materials provided by Coors. Sheets and channels are placed in alternate layers at 90° orientation in stacks and fired to produce a monolithic ceramic structure. Problems with delamination of the ceramic strips have slowed the development of this type of filter by Westinghouse.
- Blasch: Owns a proprietary injection molding process which can be used to fabricate a monolithic cross flow filter. This filter is similar in design and function as the Coors cross flow filter manufactured for Westinghouse by Coors. (Larsen, 1995 and 1996)

- CeraFilter: Similar to a cross flow filter, the CeraFilter Ceramic Monolith Filter is a porous honeycomb monolith made from a Corning ceramic body and EX-80 cordierite material coated with a fine particle filtration layer. CeraFilter Systems is a joint venture between CeraMem Separations, Inc. and Foster Wheeler Energy International, Inc., formed in 1994 to use the background of both companies to develop hot gas cleaning systems for coal and biomass conversion processes.(Proceedings, 1992; Bishop B. and Raskin, N., 1996)

3.2.5 Sintered Metal Filter Developers

Pall Corporation is developing metallic filters for high temperature application. The two programs presently envisioned are:

- Pall - Iron Aluminide: Sintered metal iron aluminide. Alloy is resistant to corrosion by sulfur compounds.
- Pall - Stainless Steels: Sintered stainless steel for application in IGCC downstream of a desulfurization system. Stainless filters were tested at the Waltz Mill gasifier. At an operating temperature of 675°C (1250°F) and with 600-3000 ppm sulfur the filters failed. When tested with less than 30 ppm sulfur in the gas stream the filters performed satisfactorily.

There is a set of test specimens which have been tested at the Dakota gasification testing site, which includes PSS 310SC (modified 310S alloy), PSS 310SC heat treated, PSS 310SC-high Cr, PSS 310SC-high Cr heat treated, PSS Hastelloy X and PSS Hastelloy X heat treated. (Bevan and others, 1995)

3.2.6 Granular Bed Filter Developers

Granular bed filters have been used to filter hot particulate at temperatures above 425°C (800°F) for over 80 years. Fluidized, packed or moving bed filters are an option for both PFBC and IGCC conditions. Testing was done in Japan by the Coal Mining Research Center at the Yubari fluidized bed test facility at IGCC conditions, using iron oxide for desulfurization. (Gilbert/Commonwealth, 1993)

In addition to the work done in Japan, Combustion Power Company (CPC) and Westinghouse have been developing versions of a granular bed filter in the United States, sponsored by DOE.

- Combustion Power Company (CPC): A granular bed filter using mullite spheres. Presently testing is being done on the use of materials that are chemically or catalytically reactive to remove additional

contaminants. Proof testing of a large CPC granular bed filter is scheduled to be performed at the Wilsonville Test Facility, at both oxidizing and reducing conditions in the KRW transport reactor, and these tests should provide data on which commercial offerings can be based. (Wilson and others, 1995) In addition to particulate removal, granular bed filters also offer the capability to remove other contaminants by the use of reactive or catalytically active bed material. A program to research and develop this capability is presently ongoing by CPC, and is scheduled to be completed by the end of 1996.

- Westinghouse: A Standleg Moving Granular-Bed Filter system is being developed to provide an alternative to the ceramic barrier filters presently in use on hot gas cleanup systems for PFBC and IGCC. The Westinghouse system has been tested at a bench scale facility both in a cold flow setup and a high temperature, high pressure rig, as part of an ongoing development program. A conceptual design and cost estimate was also made to allow comparisons between this technology and the ceramic barrier filters, which showed that the two technologies were economically comparable. No future test work is scheduled. (Newby and others, 1994)

In general, granular bed filters are less efficient than barrier filters and operate with higher pressure drops. Testing at Wilsonville should resolve these concerns.

3.2.7 Electrostatic Precipitator

Electrostatic precipitator concepts have been designed and tested in a series of experiments since 1962. Collection efficiencies between 95% and 99.9% have been achieved under varying circumstances. Problems with materials of construction, electrical power densities, corona levels and particulate agglomeration have been encountered and in some cases resolved. However, problems remain and there is presently no active, ongoing program to resolve these issues.

3.3 Test Results at HTHP Conditions

Testing of devices to remove particulates from gasifier and PFBC gas streams has been done for over 15 years. Testing in the mid 1980s was done at NYU, Curtiss-Wright and other smaller PFBC facilities. This work provided the basis for the present programs. In this section a summary of recent test work will be given along with brief descriptions of the results. Included will be sections on the fundamental work to characterize ash and measure filter cake parameters, the test work on ceramic and other type of materials used for filtration at high temperature and pressure and a review of recent or planned slipstream and pilot plant testing.

3.3.1 Characterization of Particulates and Filter Cakes

The characterization of particulates from gasifiers and PFBCs, and of the resultant filter cakes on barrier filters can be used to predict performance of filters using fundamental mechanisms for particle separation and filter pressure drop. If empirical data from operating units can be correlated with theoretical mechanisms, operation can be predicted and filter designs can be done with more confidence and eventual lower cost.

Prior to 1992, a limited amount of work was done to characterize particulates from gasifiers and PFBCs. Dust was collected from PFBC test units (Curtiss-Wright, NYU, Grimethorpe) and was analyzed mostly for particle size. This material was saved and used in tests of filters with simulated flue gases. Samples of dust from gasifiers were also saved and analyzed, but much of this information was proprietary. Westinghouse and Southern Research Institute (SRI) analyzed particulates from ceramic cross flow filter tests at the Texaco sub-pilot scale entrained bed gasifier. SRI also started a data base for both PFBC and gasifier particulates funded privately and by the U.S. DOE.

Additional work was done by CRE (Cahill and others, 1995) in the U.K. gasifier test facility, Karlsruhe (Berbner, 1995; Pilz, 1995) and by Shell International at their demonstration plant in Houston, Texas (Phillips and others, 1993; Salter, 1995). Recently, investigations and research by DOE METC have accelerated at the laboratory level as a result of filtration difficulties and problems experienced at filter test facilities.

Table 3-2
Westinghouse PFBC, Hot Gas Filter Cake Observations

	AEP Tidd Brilliant, OH			FWDC Phase 2 Livingston, NJ	Ahlstrom Pilot Karhula, Finland
Cyclone:	Yes	Cyclone Detuned	No	No	No
Fly Ash Size: (mean, μm)	1-3	5-7	25-30	5-25	12-22
Dust Loading: (1000 ppmw)	0.5-1	3-4	15-20	2-30	4-18
Permeability: (10^{-10} lb/ft)	0.2-0.6	1-2	5-6	2-5	2-6
Pulse Frequency: (1/hr)	1-2	2-4	4	0.5-3	1-3
Occurrence of Bridging and Hard Cake:	Temp >1400°F	Less Severe	Very Little	Temp >1600°F	Very Little
Vessel Drainage Performance	Poor	Little Problem	Good	Periods of Poor Performance	Good

Westinghouse completed their Integrated Low Emission Cleanup System (ILECS) study (Newby and others, 1995) in 1995, one phase of which focused on filter cake characteristics from PFBCs. They concluded that adverse filter cake behavior in PFBC barrier filters was a result of calcium-constituent sintering. This condition could be alleviated by reducing temperature, reducing partial pressures of CO_2 and SO_2 , and using dolomitic limestone instead of calcitic limestone in the PFBC. Table 3-2 provides filter cake data from Westinghouse studies along with fly ash particle size, dust loadings entering the filter, and other information concerning filter operation at three test facilities: Tidd in Ohio, Foster Wheeler (FWDC) in New Jersey, and Karhula in Finland.

Southern Research Institute (SRI) currently is continuing patch testing of various filter media and analyzing ash samples. They are also conducting ash analyses and developing field sampling techniques.(Starrett, 1996 and Pontius, 1966)

The University of North Dakota Energy and Environmental Research Center (UNDEERC) is being funded by EPRI, U.S. DOE, and others to generate a data base that will characterize the chemical and physical properties of ash and char. They also conducted lab-scale tests to support predictive models.(Dockter and others, 1996)

Table 3-3 (Newby and others, 1995) summarizes PFBC fly ash characteristics from PFBC test facilities.

Table 3-3
PFBC Fly Ash Characteristics

PFBC Source	Mean Diameter(μm)	Bulk Density(gm/cc)	Ca Content (wt%/ Ca-Sulfation (%))
<u>Tidd bubbling</u>			
Fine:	1-3	0.35	8/55-82**
Cyclone detuned:	5-7	NA	9/NA
Cyclone drain*:	10-20	NA	10/50
Cyclone bypassed:	25-30	NA	NA
<u>Karhula circulating</u>			
I	20-40	0.45	5-7/35-70
II	Finer than <u>Karhula I</u>	NA	10/90
<u>Grimethorpe bubbling</u>	1.3	0.38	5-12/40-80
<u>FWDC circulating</u>	20-40% >44 μm	0.45	20-40/20-30
*: mixture of 50% cyclone drain and 50% hot gas filter fine ash drain **: 18-25% of the calcium found in the form of $\text{CaMg}_3(\text{SO}_4)_3$ NA: Not available			

There is less data from the gasifier test facilities. Table 3-4 provides some gasifier particulate data obtained from three gasifier systems. In the fourth column "relative cleaning pulse intensity required," the term "Low" relates to a pressure difference around 5 psi (35 kPa), and "High" is 30 to 40 psi (210 to 280 kPa), indicating the relative difficulty of removing filter cake from barrier filters.

Table 3-4
Gasifier Particulate Data

<u>Gasifier</u>	<u>Cake Bulk Density (gm/cc)</u>	<u>Mass Mean Particle Size (micron)</u>	<u>Relative Cleaning Pulse Intensity Required</u>
Fluid Bed Gasifier	0.35	7.3	Low/Medium
Entrained Bed Gasifier	0.20	3.5	High
FW Carbonizer	0.20	4.5	Very High

Even though gasifier particulates are not as well characterized as PFB or PC combustor ash, it is generally known that they are irregular in shape, have more surface area, are smaller in size, and are less cohesive than PFBC ash. They also differ depending on gasifier type, coal type gasified, operating conditions, and whether limestone is added to the gasifier. PFBC ash contains sulfates (rather than sulfides in gasifiers) and can be more easily filtered than gasifier particulates. The shape of the PFBC ash is not as spherical as PC combustor ash, but not as irregular as gasifier ash.(Newby, 1995)

3.3.2 Characterization and Development of Filters

The durability of ceramic filters is affected by process gas characteristics and operating conditions. Gases that chemically attack materials are oxygen, alkali metals, steam, and reducing gas constituents. Physical damage occurs from thermal shock, thermal fatigue and mechanical strength degradation due to cyclic variations in temperature (during blowback and shutdown) and cyclic changes in gas flow direction. Much research has been done and is continuing to be done to determine the chemical and thermal factors that degrade ceramic filters.

Many failures of candle filters during pilot and demonstration tests have been attributed to abnormal or unusual operating conditions. As a result, there is some question as to the life-limiting factors causing the failures in actual plant environments. Much laboratory work however has contributed information on why commercial filters degrade. Following is a summary of recent work characterizing and screening filter material.

3.3.2.1 Westinghouse

Westinghouse has been involved with evaluations of ceramic materials in both gasifier and PFBC environments and in the field and laboratory. They have tested materials for the cross flow filter and the candle filter. After many hours of exposure at different PFBC conditions they concluded that alumina/mullite and clay bonded silicon carbide materials lose strength until a "conditioning" state is reached. In general, however, the bulk material properties appear to be relatively stable with residual bulk strength sufficiently above any steady state stresses expected to be imposed on the filter material during normal filtration operation.

Numerous phase changes within the bulk matrix or binder were also experienced. Field testing has indicated that oxide based materials are more susceptible to thermal shock. Clay bonded silicon carbide has a higher thermal shock resistance but is more susceptible to high temperature creep. Similar negative results were experienced when ceramic materials were subjected to lab tests done with simulated gasifier gases. They have additionally concluded that further work is needed to modify materials to enhance resistance to thermal fatigue and shock characteristics.

Clay bonded silicon carbide candle filters were tested for up to 6,000 hours at Tidd and 2,000 hours at Karhula. These filters have a tendency to creep at test conditions above 1400°F. They also suffered some micro-structural changes and strength degradation. These filters also had brittle failures at both test sites. New filter designs using different clay binders are being tested. SRI has determined during their materials research work that creep occurs at $<10^{13}$ cp viscosity. At 1600°F all of the clay binders studied had viscosities less than this value (Pontius, 1995). As a result of this work, different binders were found with higher viscosities at high temperatures and these are being evaluated at Karhula. Modified candle filters made of clay bonded silicon carbide and alumina mullite have been developed with characteristics that will minimize problems encountered in initial testing and are presently undergoing testing at Karhula and at Westinghouse Science and Technology Center in Pittsburgh, Pennsylvania. (Alvin and others, 1995a, 1995b and 1996)

3.3.2.2 Coors

Alumina mullite candle filters were subjected to over 700 hours of testing at Karhula. An initial loss in the bulk strength was first experienced (50 to 100 hour operation) followed by what appears to be a stabilization in the bulk material strength. This strength reduction was principally attributed to thermal fatigue of the alumina/mullite matrix as a result of the cold pulse-gas cleaning. Following the 716 test hours, the filter matrix was identified to be nearly completely crystallized.

In general, the bulk material properties of the alumina/mullite matrix appear to be relatively stable with residual bulk strength sufficiently above any steady state stresses expected to be imposed on the filter material during normal filtration operation. This type will be again tested at Karhula at PFBC conditions in 1996 for up to 1500 hours. (Lippert and others, 1995)

3.3.2.3 Industrial Filter and Pump (IF&P)

IF&P tested oxides of silica, mullite, alumina, yttria, ceria and zirconia for strength and density, and based on the results, silica, mullite, alumina and yttria based materials were selected for further development. In addition, two approaches were developed for a different type of internal reinforcement. One was based on a cylindrically woven coarse Nextel™ sock and the second was based on a formed cylinder of continuous fiber ceramic composite (CFCC). These have also shown promise and will be further developed. (Eggerstedt, 1995)

IF&P has constructed a filter vessel for Wilsonville which consists of a single tube sheet holding 90 candles. There are six plenums each containing 15 candles that will be blown back simultaneously. Three modes of testing were proposed to be done: 540°C-870°C (1000°F-1600°F) for PFBC, 540°C-980°C (1000°F-1800°F) for gasifier, and 540°C-790°C (1000°F to 1450°F) for the carbonizer. The IF&P filter vessel is sized to match the gas flow on the M. W. Kellogg Transport Reactor and can be moved there for testing.

3.3.2.4 3M

A rigid ceramic composite filter of 30% NEXTEL 312 ceramic fiber and 70% silicon carbide was developed by 3M. The filters are a fibrous substrate, chemically vapor infiltrated (CVI) with silicon carbide to form a toughened, rigid composite structure. Maximum recommended operating temperature is 1200°C (2200°F). Tests were performed at 710°C (1310°F) using a test rig with a gas burner and measured particle introduction, which simulated coal gasification conditions. Tests were run from 6 hours to 100 hours, and solid loadings and velocities were varied. Results indicated that the filter would operate well under simulated conditions and produced excellent filtration efficiencies. A second set of tests was run on another set of filter elements at a different location utilizing operating characteristics simulating PFBC operation, at 815 - 830°C (1500-1536°F) for 175 hours. In addition, 14 hours of thermal transient testing were done. The filters performed as expected with no failures. (Ergunder and others) Currently, tests are being performed at the Karhula CPFBC pilot plant with new advanced versions promising longer life at PFBC oxidizing conditions. Candles will also be tested at a Japanese gasifier pilot plant in 1996. (Fischer, 1996)

3.3.2.5 Southern Research Institute

SRI has provided property measurements and exposure to the hot gas filtration operating environment for Refractron and Schumacher clay-bonded SiC materials and Coors alumina mullite. Results have shown that these materials are susceptible to micro cracking on the inner bore from the thermal stress generated during pulse cleaning when the temperature drop on the I.D. of the candle is on the order of 38°C to 93°C (100°F to 200°F). Tensile creep tests indicated that these clay bonded materials creep at temperatures of 760°C (1400°F) or greater. Neck cracks and large deformations on bowed candles removed from Tidd and Karhula have been explained by the creep test results. Degradation of mechanical properties has been measured in clay-bonded candle filters after exposure in Tidd and Karhula.

New Schumacher and Refractron candle filters have also been tested at SRI. These materials have a different binder intended to decrease the creep rate. Test results indicated that both materials have a significantly lower creep rates than the previously tested material up to 870°C (1600°F). The test results also indicated that the Schumacher FT20 material withstood temperature differences up to 120°C (250°F) without micro cracking while the Refractron 326 material withstood temperature differences up to 160°C (320°F). (Spain, 1996)

Additional advanced materials are also currently being evaluated. Four materials currently in evaluation are IF&P Fibrosic material, Dupont Lanxide silicon carbide and PRD 66 composite materials, and 3M filter material. Initial screening of the materials consists of tensile and thermal expansion measurements. These properties provide an estimate of thermal stress performance in the hot gas cleanup environment. Tensile strength will be measured after exposure to elevated temperature to provide an indication of whether a material can survive at elevated temperatures for long time periods. After these materials are used in a hot gas filtration environment, residual properties will also be measured. (Starrett, 1995)

3.3.2.6 Advanced Filter Material Program

A program to design, build, and test a group of advanced filters is presently underway at METC. The purpose of this program is to develop high temperature filters that are resistant to brittle failure and thermal stress damage. Ceramic materials, including composites, and corrosion resistant metals, are being used to fabricate damage tolerant filter elements. The program is designed to build on work done under other government programs, such as iron aluminide development at ORNL and ceramic composite development under DOE's Continuous Fiber Ceramic Composite (CFCC) Program. In addition, support of a hot gas filter system supplier is required for each project to ensure a clear commercialization path. The program explores a diversity of approaches including metals, oxide ceramic composites, non-oxide ceramic composites, and a unique ceramic with composite like properties. The program's goal is to have each

contractor produce filters and expose them to corrosion testing and high-temperature, high-pressure, simulated filtration testing. Each project has an option to produce 50 filters to be made available for pilot scale testing. Project participants include Babcock and Wilcox, Westinghouse-Techniweave, Pall Corporation, Dupont Lanxide Composites, and Textron.

The objective of the Babcock and Wilcox project is to fabricate and test oxide-based, continuous fiber ceramic composite hot gas filter elements for advanced power generation systems. In Phase I, porous composite fabrication technology was used to fabricate porous composite tubes containing either Nextel 610 or Almax alumina fibers as reinforcements. Twelve inch long sub-scale filter tubes were then fabricated and tested. Evaluation of these samples included a static exposure test in a coal combustion environment. Results of this testing were used to identify a composition for full-scale filter fabrication and testing in Phase II of the program. (Wagner and Weitzel, 1966)

The specific objectives of the Pall Corporation project are to develop corrosion resistant alloys and manufacturing processes to fabricate iron aluminide filter elements, for application in IGCC power generation systems. A short-term, laboratory exposure apparatus supported by other tests will be used to identify the most promising candidate. The objectives of the second work phase are to demonstrate long term corrosion stability for the best candidate, and finally, produce fifty filter elements for pilot scale testing. (Hurley and others, 1996)

Filter elements are made using their standard seamless tube fabrication process, which produces an intrinsically uniform and inexpensive medium. Three iron aluminide filter elements have been provided to METC for inclusion in gasification tests. A promising alloy and a satisfactory sintering cycle were chosen recognizing that neither has been optimized as yet.

Oak Ridge National Lab is supporting Pall Corporation's development of iron aluminide filters. The purpose of their work is to determine the usefulness of this filter material under combustion conditions. Corrosion performance will be evaluated using gravimetric data, optical metallography, x-ray diffraction, and scanning electron microscopy with associated energy dispersive x-ray analysis. Corrosion exposures will be conducted at 650°C (1200°F), 750°C (1380°F), and 900°C (1650°F) so that the temperature range encompasses both first and second generation PFBC hot gas filtration conditions.

The objectives of the Westinghouse-Techniweave project are to develop and test an oxide-based CFCC filter element. Continuous fibers are woven in a pattern that provides fiber reinforcement in all three directions, as opposed to other fibers processing techniques such as filament winding which provide reinforcement in only two directions. The fiber preform is infiltrated with a mullite sol to provide a mullite matrix. Fibers being evaluated include Nextel 550, Nextel 610, and Nextel 720. (Lane and others, 1996)

The objective of the Dupont Lanxide Composite project is to improve and test a filter technology that has been under development and is near a commercial state of readiness. This unique filter materials, named PRD-66, is fabricated by winding fiber glass into a cylindrical shape and infiltrating it with an oxide slurry. The filter is fired at high temperature so the infiltrated oxide reacts with the fiber glass to produce an all ceramic oxide composition. This composition experiences microcracking during processing which gives the material a degree of thermal shock resistance. This is not a fiber reinforced material, and is therefore relatively inexpensive and easy to manufacture. Failures of this material occurred during testing at the Tidd PFBC Demonstration Facility, and the project has been redirected to assess these failures and provide an improved filter. Currently work is focused on filtration membrane improvement, flange strengthening, and elimination of internal delaminations. (Chambers and Garnier, 1996; Chambers, 1966)

The focus of the Textron project was to develop a non-oxide CFCC hot gas filter. Textron investigated a nitride-bonded silicon carbide material reinforced with their SCS-6 silicon carbide monofilament. Textron was not able to balance acceptable permeability with acceptable strength, and the project is being terminated at the conclusion of the base program. (DiPeitro, 1996)

3.3.2.7 DOE CFCC Program

High temperature filter development work is also ongoing under the DOE Office of Industrial Technology's Continuous Fiber Ceramic Composite (CFCC) program. Within the CFCC Program, Atlantic Research, Babcock and Wilcox, Dupont Lanxide Composites, and Textron are developing processing methods to produce CFCC high temperature filters. Each of these CFCC participants has identified hot gas filters as a potential produce for their company. In the cases of Babcock and Wilcox and Textron, acid processing and materials development work provides the basis for more focused filter development and testing under the METC program. In the cases of Atlantic Research and Dupont Lanxide Composites filter development and testing work is a significant part of the CFCC program. Dupont Lanxide Composites is developing a non-oxide filter element. This filter is fabricated using Nicalon silicon carbide fibers that are infiltrated with a CVI silicon carbide coating. Atlantic Research is using CFCC and CVI technology to develop an improved conventional filter fabricated by Industrial Filter and Pump. (Richlen, 1995)

3.3.3 Pilot Plant Testing and Demonstrations

The successful research and development projects feed into the slipstream/pilot plant testing programs. In the U.S., pilot plant activities for PFBC are in abeyance with Tidd shut down and the Power Systems Development Facility just starting up. A PFBC CCT demonstration plant is under negotiations and should be announced shortly. Outside the U.S., the Karhula pilot plant and the Wakamatsu demonstration plant are testing high temperature filters.

For IGCC this is a defining year with three large scale demonstration plants, Wabash, Tampa Electric Company, and Pinon Pine, all starting up in 1996. All three will utilize candle filters for fuel gas particulate removal although the Wabash filter operates below 315°C (600°F). Following is a brief summary of the filter test work at the major test facilities.

3.3.3.1 Tidd

The Tidd facility was a 70 MWe PFBC pilot plant installed at an Ohio Power Company power plant as a CCT demonstration project. In 1992 a hot gas filter designed by Westinghouse was installed and tested until 1995. The vessel contained 384 candles and was capable of cleaning a slip stream 1/7 of the total flue gas flow. The majority of the test work was done with silicon carbide candles; however, some advanced materials were also tested.

This program provided valuable information for the future design and operation of ceramic barrier filters in a PFBC flue gas environment. The most important conclusions reached from this program are listed below.(Tidd, 1995)

- The basic design of the candle-based Advanced Particulate Filter (APF) was structurally adequate. The hot metal structures of tubesheet, plenums, and candle holders operated without problems.
- Clay-bonded silicon carbide candle material exhibited approximately 50% loss of strength after 1000-2000 hours of exposure to the PFBC environment. The strength level stabilized upon further exposure time.
- Nearly all of the silicon carbide candle breakage observed in this program was attributed to ash bridging in the APF. Ash bridging was strongly affected by the size and temperature of the ash entering the filter. Ash from a partially detuned cyclone (about 7 microns) was more easily removed than the smaller ash, but still difficult to remove at operating temperatures over 790°C (1450°F). Ash above 27 microns was easily removed and did not tend to bridge.
- It is important to prevent ash from entering the inside of the filter candles to avoid blinding them on the inside surfaces which have larger pore size than the outer surfaces. Also, ash accumulation in the inside bottom of candles can induce cracking in the candles.
- It is important to have reliable continuous ash removal from the filter. Ash buildup in the particulate filter hopper resulted in candle breakage.

3.3.3.2 Karhula

Ahlstrom Pyropower has designed and built a pilot-scale 34 MM Btu/hr Pressurized Circulating Fluidized Bed (PCFB) Combustor Ceramic Barrier Filter Testing Facility in Karhula, Finland (Lippert and others, 1995). A key aspect of the PCFB testing is the evaluation of the ceramic barrier filter technology.

In 1989, Electric Power Research Institute (EPRI) and Pyropower Corporation (PPC) signed an agreement for EPRI's support in the testing of Asahi Ceramic Tube Filters (ACTF) in Ahlstrom's 10 MW_{th} PCFB pilot plant. The testing of ACTF was completed in June 1992. PPC, in cooperation with American Electric Power Service Corporation (AEP), the U.S. Department of Energy (DOE), Electric Power Research Institute (EPRI), and Westinghouse Electric Corporation (WEC), have developed a program for testing of the Westinghouse Candle Filter (WCF). The Westinghouse Candle Filter is being tested in tandem with the PCFB combustor. The agreement between EPRI and PPC was modified in the summer of 1992 to include continued support of EPRI for the WCF testing. The design and supply of the Westinghouse candle filter unit was conducted in support of a cooperative agreement between the American Electric Power Service Corporation and the U.S. Department of Energy.

The PCFB facility consists of five major components: compressor, circulating bed combustor, barrier filter, flue gas cooler and pressure reduction station. High pressure air is used to burn coal in the circulating bed combustor unit. The Westinghouse candle filter unit installed in the Ahlstrom facility was backfitted to the pressure vessel previously housing the Asahi ceramic tube filter unit. The Westinghouse unit consists of a single filter cluster containing 128 candle elements that are arrayed on three plenums.

During testing, extended, trouble-free operating periods have been achieved during which the candle filter unit has demonstrated excellent particle collection efficiency and stable filter pressure drop. Test conditions have extended over a wide range of coal/sorbent types and gas temperatures. The scale-up, mechanical structure, and candle sealing features of the design have been evaluated and shown to meet commercial PCFB requirements.

Currently in the Karhula facility advanced silicon carbide candles with an improved clay binder capable of operating at 850°C (1560°F) without exhibiting creep are being evaluated by Westinghouse, Schumacher and Pall. Post test evaluation of these materials will be conducted by Westinghouse. (Lippert, 1996; Sawyer, 1996; Seymour, 1996)

3.3.2.3 Energy and Environmental Research Center (EERC)

A new hot-gas filter program was started in January 1995 as an addition to the DOE-METC and EERC Cooperative Agreement. This new subtask has also supported upgrades to the Transport Reactor Development Unit (TRDU) and will support three 200-hour filter tests in the next 21 months. (Mann, 1995)

Two test campaigns were conducted during the spring of 1996. During this time, 138.5 hours of coal feed and 107 hours of gasification were achieved, with the system gases and fly ash passing through the filter vessel during the test campaign. The candles were backpulsed 70 times with no major candle failures. The only observed problems were a leak around the ceramic tube sheet and three of the candles not sealing in the tube sheet correctly. The leakage around the candles is the result of mixing four different candle types in a tube sheet with a common holddown plate. One bridge was observed between two adjacent candles. It appeared that the bridge was the result of a slightly bowed candle coming close enough to the adjacent candle that a bridge was able to be formed. (Swanson and Ness, 1966)

3.3.3.4 Wakamatsu

The Asahi tube filter is now being tested at the Wakamatsu PFBC demonstration plant based on the first generation technology developed by ABB Carbon. (Goto, 1995) The tube filter consists of two vessels each containing 85 tubes. The two filters will clean the total amount of flue gas at 860°C, 12 atm, 250,000 m³/h (1580 °F, 162 psi, 147,000 cfm). A low expansion cordierite has been used for the tubes to help prevent tube failures due to excessive blowback. The seals were also redesigned. In previous tests carbon/char carryover to the tubes caused fires. This has been apparently alleviated by a change in the cyclone pre-cleanup system. Only primary cyclone cleanup is used. These vessels are the largest high temperature, high pressure filter vessels in the world. Initial results from the tests were provided by B&W, the U. S. licensee of this technology (Weitzel, 1995). At a temperature of 830 °C (1525°F) and pressure of 10 atm the filter operated successfully for 50 hours with acceptable pressure drop. The PFBC was shut down because of problems with hot piping not related to filter operation. After restart, one of the tubes broke then two more suffered damage apparently caused by combustibles overheating the tubes. The test period has been extended beyond the original shutdown date of April 9 to make up for lost time due to the unplanned shutdown.

3.3.3.5 Power Systems Development Facility

The Wilsonville Power Systems Development Facility (PSDF) is a joint, cost-shared effort of the United States Department of Energy (DOE), the Electric Power Research Institute (EPRI), M. W. Kellogg, Foster

Wheeler USA, Westinghouse, Southern Research Institute, Combustion Power Company, and Industrial Filter and Pump.(Pinkston and others, 1995) Its purpose is to address the research and development needs for advanced coal-based power generation systems. Operated by Southern Company Services (SCS), the \$200 million facility will be used to test advanced power system components, evaluate advanced configurations, and assess the integration and control issues of these power systems.

Initially the facility will be a resource for long-term testing and performance assessment of hot gas particulate removal in IGCC and PFBC system environments. The plan is to test four different particle control devices (PCDs) at the PSDF. Other types of PCDs may be tested later. Initial plans call for testing a barrier filter supplied by Westinghouse and a granular-bed filter supplied by Combustion Power Company (CPC) on the MWK transport reactor system. The FW carbonizer and CPFBC will be equipped with candle filters supplied by Industrial Filter and Pump (IF&P) and Westinghouse. The two filters in the transport reactor train and the filter on the carbonizer are designed to be interchangeable to allow testing of these three PCDs on both gas generators. Because of the delay in the construction of the FW test facility, the IF&P PCD will be tested on the transport reactor system. The transport reactor can operate in either an oxidizing or reducing mode over a range of temperatures. Thus many of the temperature dependent issues with ceramic filters should be resolved here.(Longanbach, 1995)

3.3.3.6 Tampa Electric Company

The overall project integrates two major technologies - coal gasification and combined cycle power generation into an IGCC power plant. This allows the use of low cost coal with the efficiency of the combined cycle. This will provide a system that is more efficient than a conventional coal-fired unit. With the exception of the new hot gas cleanup (HGCU) technology, only commercially available equipment was used for this project. The approach supported by DOE is the highly integrated configuration of these commercially available pieces of hardware or systems in a new arrangement which is intended to optimize cycle performance, cost and marketability at a commercially acceptable size of nominally 250 MW_e (net).

This project is expected to demonstrate the technical feasibility of a commercial scale IGCC unit using hot gas clean-up technology. The hot gas cleanup systems will be tested on a 10 percent slip stream. In addition, demonstration of the oxygen-blown entrained-flow IGCC technology is expected to show that such a plant can achieve significant reductions of SO₂ and NO_x emissions when compared to existing and future, conventional coal-fired power plants.

The project's construction and start-up is expected to be completed by about September 15, 1996. Following will include a two year development of operating and maintenance data and performance

parameters on four different types of coal. In addition to the high efficiency primary cyclone being provided upstream of the hot gas desulfurization system, a high temperature barrier filter will be used downstream of the HGCU to protect the combustion turbine. A Pall 56 candle sintered metal filter will be utilized. (Sawyer, 1996)

3.3.3.7 Piñon Pine

Sierra Pacific Power Company (SPPC) is building an IGCC power plant. The project was selected by the U.S. Department of Energy (DOE) for funding under the Clean Coal Technology Program. The project includes the design, engineering, procurement, construction, and testing of a nominal 800 ton per day coal-fueled IGCC plant generating a nominal 95 MW_e net. The facility, which will be owned and operated by SPPCo, will be built at their Tracy Station some 20 miles east of Reno, Nevada.

The project will utilize the Kellogg-Rust-Westinghouse (KRW) fluidized bed ash agglomerating gasifier in an air blown mode. Hot gas cleanup will be accomplished by employing ceramic candle filters and a mixed metal oxide sorbent for sulfur absorption. The ceramic candle filter system will be supplied by Westinghouse using Refractron candle filter elements.

Compared with conventional oxygen-blown gasification systems using cold gas cleanup, the advanced air-blown design offers significant potential for reducing complexity and consequently capital and operating costs. Construction began in early 1995, and will be completed in late 1996. (Lippert, 1996)

3.3.3.8 Lakeland

The first commercial PFBC plant will be a CCT demonstration for the City of Lakeland. This project was developed by consolidating two earlier CCT proposals: the Round III DMEC-1 PCFB Demonstration Project, and Round V Four Rivers Energy Modernization Project. The consolidation of these two have been relocated to the City of Lakeland's C.D. McIntosh, Jr. Power Plant Unit 4. The Lakeland PFBC project received October 29, 1996 approval by the Assistant Secretary for Fossil Energy, with contract signing in December of 1996. Foster Wheeler Energy Corporation is the owner of both PCFB technologies involved, since Foster Wheeler bought the former Ahlstrom Pyropower subsidiary and Pyropower's PFBC combined-cycle technology.

The new PFBC CCT project will be implemented in two phases:

- A 157-MW_e non-topped PCFB, which will begin operation in 2000, which is expected to have an efficiency of approximately 40 percent.
- If successful, a 12-MW_e topping cycle will be added, converting the system into an APFBC, which would boost the total system to 169 MW_e output and the efficiency to about 47 percent.

The consolidation of both projects is estimated to save \$158 million. The total project cost will be \$405.3 million. DOE's share will decrease by \$33 million, for a total of \$202.5 million.(Clean Coal Today, 1966)

3.4 Technical Issues

Characterization testing of filter elements and pilot scale testing of filter systems have indicated some potential problem areas which can affect filter element life or filter operation. Thick ash deposits have formed bridges from passive surfaces to the filter material and between filter candles. A significant number of ceramic filters have broken in various experimental and demonstration devices, especially during the long-term testing of the candle filter system at the Tidd station. Similarly, there have been failures, although not as regularly at Karhula, in other pilot plants, and in tests of small discs or "patches" of filtration materials. (Pontius, 1995).

3.4.1 Filter Material Issues

At this time, the five candle filter materials that are considered commercial experienced operating problems based on tests in the field and laboratories:

- Coors Alumina Mullite: susceptible to cracking by thermal shock
- Refractron Clay Bonded Silicon Carbide: the original binder experienced creep above 760°C (1400°F); a new binder is under evaluation
- Schumacher Clay Bonded Silicon Carbide: the original binder would creep above 760°C (1400°F), a new binder is under evaluation
- Industrial Filter & Pump Fibrosic: material is weak and has failed under lab tests
- Pall Stainless Steel: may not be resistant to sulfur concentration spikes or continued H₂S exposure above 30 ppm.

Although ceramic candle filters remain among the most promising candidates for hot gas particulate removal systems, the problems with both durability of the candles and long-term buildup of dust deposits must be resolved. Material scientists are identifying and developing new filter materials and system engineers are developing design criteria and other means to increase durability and to avoid the formation of excessive dust accumulation.

The critical filter material properties are tensile strength retention and tensile creep, or micro crack stability. These properties must be determined on materials previously exposed to the operating environment or measured under the conditions of normal operation. Projections of a material's ability to

survive for a long time in the operational environment requires either long-term data under operational conditions or limited data supported by information on the micro-and macrostructures, chemical makeup, and other basic properties that can be used to develop predictive models.(Pontius, 1995) Although there has been work sponsored by DOE/METC concerning fundamental parameters of filter cake character, separation stress, and particle characteristics, more data is needed to fit models which can predict what happens when particles are collected and blown off of barrier filters. Such data is difficult to obtain in laboratories and in the field. (Filter, 1995)

A coordinated program is in place to resolve many of these fundamental technical issues. This program has led to the recent advances in filter element development and feeds into the pilot plant testing and demonstration programs. Progress has been reported in both reducing creep above 760°C (1400°F) and increasing the ΔT for microcracking (Spain, 1996). These developments will be verified in Karhula tests underway and at the PSDF .

3.4.2 IGCC and PFBC Particle Collection System Issues

Ceramic candle filters are being used in IGCC systems downstream of syngas coolers below 300°C (572°F) to remove fine solids from the full stream of syngas at the Buggenum and Wabash River demonstration plants. For temperatures between 300°C and 550°C (572°F and 1022°F), candle filters made of silicon carbide should be satisfactory for particulate removal in gasifier fuel gas streams. Numerous pilot plant tests have shown that these filters will perform efficiently and can withstand the gas composition conditions. (Salter, 1995; Ito, 1995) Long term durability has not yet been demonstrated, but the Piñon Pine IGCC demonstration plant should provide this data.

Simultaneously, new ceramic fiber materials are being developed that can be used if the current SiC types do not prove acceptable for IGCC use. The testing at Wilsonville will also add to the development of not only candle filter materials but other types of filter media that may reduce capital and operating costs. As operating data becomes available through the CCT demonstration plants, the upper temperature limit of ceramic filters in reducing conditions should increase. Filters can already be recommended for use at 650°C (1200°F).

Some conclusions can be made based on the data that is available on the status of particulate removal for PFBC conditions. Between 650°C and 760°C (1200°F and 1400°F) there is confidence that candle filter vendors would recommend a filter. This is primarily due to successful pilot plant test results in this temperature range. Other barrier filters such as the granular bed filter and cross flow filter do not have enough test data to be considered at this time. The development of advanced materials, however, is

accelerating and there is good reason to believe that these advanced versions of ceramic candle filters will perform at 845°C (1550°F) or above. In addition, fundamental research is being done which could define mechanisms of high temperature filtration. This will help in choosing materials and the design of filter systems. Also, the filter system suppliers are continually improving their filter designs. These improved designs will first appear in the CCT demonstration plants.

There are two pilot facilities which will have a great impact on the development of PFBC filters: Wilsonville and Karhula. At the demonstration level, only Wakamatsu is active and the only filter being tested there is the Asahi tube filter. Three tubes broke during a startup after an unplanned shutdown, but the tests are continuing and the test period has been extended to make up for lost time. The testing of various filters at Wilsonville and Karhula will provide design information for the PFBC Clean Coal Technology demonstration at Lakeland, FL. This project will use candle filters provided by Westinghouse for particulate control.

Much work is being carried out to investigate design and operational issues associated with hot gas filters. This includes operational experience with dusts from an increasing range of fuel types, the optimization of pulse cleaning systems to minimize thermal shock while maintaining satisfactory long-term candle permeability, and the design of the filter to maximize filtration capacity and improve gas flow. (Seville and others, 1966)

Currently vendors will recommend a filter based on an operating temperature for up to 650°C (1200°F) at reducing (gasifier) conditions, and up to 750°C (1380°F) at oxidizing (PFBC) conditions. There is a new candle element being tested for operation up to 850°C (1560°F) in oxidizing atmospheres but long term testing is needed before it is considered commercial. Candle filter element manufacturers will not guarantee a filter element unless they have control of the operating conditions. Of particular concern is the impact of the operating temperature and of the long term exposure to alkalis in the gas stream.

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4.0 STATUS OF THE TECHNOLOGY - HOT GAS DESULFURIZATION SYSTEMS

Hot gas desulfurization (HGD) for gasifier fuel gas was first considered as an application for integrated gasification with a molten carbonate fuel cell (MCFC). The MCFC operates at a fuel inlet temperature of 650°C (1200°F), and the benefits of maintaining the sensible heat of the fuel gas with HGD include higher plant efficiency, lower capital cost, and no condensed impurities in the gas. HGD research was also influenced by METC promoting the Simplified IGCC System, consisting of an air-blown fixed bed gasifier, hot gas cleanup, and an advanced turbine. Since hot gas cleanup in the range of 550°C-600°C (1000°F-1100°F) is critical to the success of the Simplified IGCC, research on HGD continued. The current DOE IGCC program calls for the inclusion of high temperature gas turbines with hot gas cleanup, and demonstration by 2010. Interim demonstrations will be conducted at the Tampa Electric and Piñon Pine CCT projects. Recent interest has also surfaced in the desulfurization of fuel gas at lower temperatures, referred to as low temperature hot gas desulfurization (LTHGD), primarily to ensure that, for extended usage at less severe conditions, sorbents will retain a larger portion of initial properties such as sulfur capacity and structural integrity.

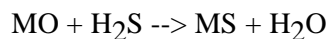
Initial testing of hot gas regenerable sorbents focused on iron oxide for fuel cell applications. When iron oxide tended to spall and lose activity, and did not achieve a low enough H₂S equilibrium concentration (100-200 ppm), research evolved to zinc-based sorbents.

In addition to sorbent development, HGD process configurations have also evolved. The fixed bed process was the original concept utilized by METC in developing concepts which use regenerable sorbents, such as zinc ferrite or zinc titanate. The process consists of pressurized fixed bed reactors that alternately absorb and regenerate. As an approach to solving some of the problems associated with the fixed bed, General Electric has been developing a novel hot gas cleanup process that consists of a moving bed absorber containing a mixed-metal oxide sorbent to remove sulfur compounds, a moving bed regenerator to regenerate the sorbent and produce a high SO₂ concentration tail gas, a regeneration gas recycle, and a solids transport system. Additional process development was supported by METC in the fluidized bed approach to HGD. The fluid bed system allows easier temperature control and more flexibility to operate continuously. Finally, recent developments include the M. W. Kellogg transport reactor as both an absorber and regenerator for HGD. The GE moving bed process will be demonstrated with a 25 MW_e slipstream at the Tampa Electric Company CCT project, and the M. W. Kellogg transport reactor will have a 100 MW_e full scale demonstration at Piñon Pine.

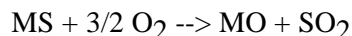
There are several approaches to sulfur fixation once the HGD sorbent is regenerated and an SO₂ stream is produced. If the HGD is utilized as a sulfur polisher when the gasifier uses a limestone or dolomite sorbent for in-situ sulfur capture, the SO₂-rich regeneration gas and the gasifier solids are fed to a sulfator where CaS is oxidized to CaSO₄ for disposal. Also, METC has sponsored the development of the Direct Sulfur Recovery Process (DSRP) by RTI, in which SO₂ with stoichiometric fuel gas is converted directly to elemental sulfur over a catalyst.

4.1 Basis of Gas Desulfurization at High Temperature and Pressure

The fundamental mechanism of desulfurization is based on the reaction of H₂S or, in significantly lesser concentrations, COS in the fuel gas with the active metal oxide in the sorbent. This can be represented by the following equation, where M is an active metal:



When the sorbent is fully loaded with sulfide, it can typically be regenerated with dilute air to produce an off-gas containing SO₂. The regeneration reaction can be represented by:



The regeneration reaction is considerably more exothermic than the absorption reaction, but significantly slower.

4.1.1 Sorbents

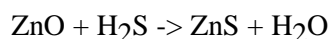
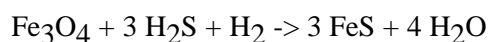
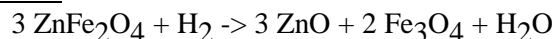
In the late-1970's, the requirement for a hot gas desulfurization sorbent to integrate molten carbonate fuel cells with coal gasification resulted in METC developing iron oxide sorbent on fly ash and silica substrates having improved strength and regeneration properties. In light of a need for a regenerable sorbent which could lower the sulfur levels to 10 ppm or less, zinc ferrite evolved as a likely candidate for testing as a regenerable sorbent. The objective was to have a sorbent which combined the low sulfur equilibrium of zinc and the regenerability of iron oxide. Laboratory development on zinc ferrite was conducted at METC through the 1980's. Testing of zinc ferrite had indicated that repeated cycling and the presence of highly reducing gas and steam in the regeneration gas caused sorbent structure to decrepitate prematurely. During the time period from 1990 to 1992, the DOE was advancing the technological capabilities of hot gas sorbents to include zinc titanate as a viable alternative to zinc ferrite. Zinc titanate and other zinc oxide-based HGD sorbents offered a more durable alternative to the zinc ferrite.

4.1.1.1 Zinc Ferrite

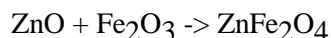
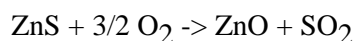
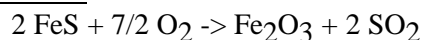
The compound zinc ferrite, ZnFe_2O_4 , formed by heating an equimolar mixture of zinc and iron oxides, combines the high sulfur affinity of zinc oxide with the good regenerability of iron oxide. The formation of zinc vapor in a reducing atmosphere is also thought to be inhibited in comparison with that of zinc oxide. Zinc ferrite also has the ability to remove sulfur efficiently in the coal gas containing greater than 20 percent moisture.

The chemical changes taking place during sulfidation and regeneration of zinc ferrite may be represented as follows:

Sulfidation



Regeneration



Removal of H_2S and COS in coal-derived fuel gas to a level of about 10 ppm can be achieved with zinc ferrite. The high steam content of the gas and catalytic nature of the ferrite promote both the COS hydrolysis and CO /water shift reactions.

Complete sulfidation on a theoretical basis results in a sulfur loading capacity of 0.4 gm sulfur per gm of zinc ferrite in its oxidized state (although in practice about 0.15 gm sulfur per gm sorbent) in the temperature range of 450°C to 650°C (850°F to 1200°F).

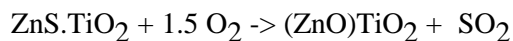
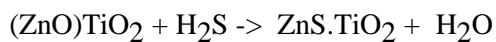
Under moderately reducing conditions such as those existing in fuel gas from a Lurgi air-blown gasifier, the hematite (Fe_2O_3) is reduced to magnetite (Fe_3O_4), the active oxide, rather than to other reduced iron forms such as carbides, which cause irreversible sorbent damage. Oxygen blown gasifiers usually require the addition of water or steam to reduce the $(\text{CO} + \text{H}_2)/(\text{CO}_2 + \text{H}_2\text{O})$ ratio to an acceptable range to prevent carbide formation.

Regeneration at temperatures below 750°C ($1,400^\circ\text{F}$) results in the formation of ZnSO_4 . Sulfate formation increases at lower temperatures, at higher pressures, and in the presence of SO_2 and O_2 in the regeneration gas. The sulfate decomposes quickly above 700°C (1300°F) in a gas atmosphere with low concentrations of O_2 and SO_2 .

4.1.1.2 Zinc Titanate

Zinc Titanate was one of a number of sorbents developed at the Massachusetts Institute of Technology to overcome the problems of zinc ferrite. In response to this, METC designated four zinc titanate sorbent formulations for further development by Research Triangle Institute (RTI). These sorbents, containing 0.8 to 2.0 molar ratios of ZnO/TiO₂ were prepared by United Catalysts, Inc. (UCI) for RTI. Preparing these sorbents is similar to making zinc ferrite. Sorbents have been prepared using both organic (0-10%) and inorganic (2-4%) binders.

The chemical changes taking place during sulfidation and regeneration of zinc titanate may be represented as follows:



The sulfidation and regeneration reactions amount to simple exchange reactions involving the ZnO portion of the zinc titanate and the sulfur. Unlike the zinc ferrite, there is no loss of hydrogen from the fuel gas during absorption and the level of reducing species in the gas is inconsequential.

Based on zinc loss and sulfidation/regeneration kinetics, the 1.5 ZnO/TiO₂ zinc titanate is the preferred sorbent for use due to its superior performance in oxygen-blown syngas (no steam required).

Complete sulfidation results in a sulfur loading of 0.24 gm sulfur per gm of fresh zinc titanate sorbent (although in practice complete sulfidation is not achieved) and it can be utilized for absorption in the temperature range of 550°C to 750°C (1000°F to 1400°F).

Due to the lack of ferrite, there is minimal catalytic activity associated with the titanate, and the CO/water gas shift reaction is less likely to occur in the absorber. COS hydrolysis is anticipated by virtue of the excess steam/COS ratio in the gas.

4.2 System and Sorbent Developers and Manufacturers

The evolution of HGD systems has followed an interesting path due to the requirement for systems to accommodate sorbents with properties and operating requirements that were also evolving. Systems evolved as a means of controlling absorption and regeneration temperatures, while either minimizing attrition losses (fixed and moving beds), or utilizing fine particulate sorbents (fluidized bed and transport reactor). As sorbents continue to be developed, the system operating parameters are adjusted to accommodate the sorbents. Therefore, the net result reflects the sorbents leading the system development. Sorbent developers have entered into agreements with sorbent manufacturers to produce both pilot and demonstration quantities of sorbents. Additional development effort has been expended on sulfur fixation in the DSRP and in developing means to sulfate the reduced solids exiting the IGCC system.

4.2.1 System Developers

This section provides a brief description of the key features and status of the four types of hot gas desulfurization reactors and processes that have been tested and evaluated for utilization in IGCC power plants. The types of reactors have evolved in two separate paths: from the fixed bed concept to the moving bed concept; and from the fluidized bed reactor to the transport reactor. Each evolutionary move has improved the operational characteristics of either the sorbent or the process.

Table 4-1 is a summary of the developmental status of the desulfurization reactors. This table describes the time frames under which the processes have been developed, and indicates the operational issues driving the evolution of the processes.

Table 4-1
HGD Process Development Status

[big landscape table]

4.2.1.1 General Electric

Moving Bed Desulfurization -- Compared to the fixed-bed concept, the moving-bed system has several potential advantages. Two vessels are used, each designed and dedicated to one function. The absorber is a counter-current flow reactor with continuous flow of coal-gas and intermittent flow of sorbent. The regenerator is a multistage, co-current reactor which allows for control of the exothermic regeneration reaction and prevents overheating, sintering, and destruction of the sorbent. The moving-bed process also uses recirculation of the regeneration gas for temperature control, and, unlike the fixed-bed concept, it offers the advantage of diluent flow continuously through a single vessel.

The moving bed concept, while offering certain process advantages, does not provide mechanical design advantages over the fixed-bed concept. High-temperature and high-pressure valves and piping are required in both cases, while the moving bed also includes hot sorbent transport equipment. The degree of difficulty in operating the high temperature, high pressure hardware is now very much reduced through successful temperature control systems.

The moving-bed concept requires a sorbent material with sufficient mechanical strength properties to allow movement through the system without excessive materials breakup or attrition that would adversely impact system economics by introducing a high sorbent makeup cost.

Testing of the pilot scale system at GE Corporate R&D has been underway since 1990, recently with the combined operation of a pressurized gasifier, hot gas cleanup system, and turbine simulator. The hot gas cleanup system also contains a circulating fluidized bed chloride removal system utilizing sodium bicarbonate to remove chloride from the coal gas. Efforts during 1995/1996 have focused on identifying and testing sorbents for use in the Tampa Electric CCT IGCC demonstration project. (GE 1996)

Also, a 4 TPD moving bed system was jointly tested by the Engineering Association for IGCC Power Systems and Kawasaki Heavy Industries (KHI) with a slipstream from the 200 TPD IGCC pilot plant at Nakoso, Japan. The operation started in February 1992 and was completed December 1995 with 1,702 cumulative hours of testing. The system utilizes iron oxide to remove both sulfur compounds and dust particles in cross-flow beds at 420°C (788°F). (Kamei, 1996)

4.2.1.2 M. W. Kellogg

Transport Reactor -- The transport reactor is the hot gas desulfurization unit to be utilized in the Piñon Pine Project. M. W. Kellogg has conducted sorbent tests at the Transport Reactor Test Unit

(TRTU) in Houston, and has gained sufficient test experience with the transport technology for other applications from the petroleum industry to utilize it at Piñon Pine. The Transport Reactor Desulfurizer is based on proven commercial technology, and has high mass throughput per capital cost. (Moorehead, 1996)

The transport reactor desulfurizer consist of a riser tube, a disengager, and a standpipe for both the absorber section and regeneration section. The desulfurizer system train is capable of processing gas equivalent to about 100 to 150 MW. For the Pinon Pine project, the absorber riser is 107 cm (42 inch) diameter by 15 meter (50 foot) high. The regenerator is a 7.5 cm (3 inch) diameter and 20 meter (70 feet) high transport reactor through which 4.54 kg/sec (36,000 lb/hr) of sorbent from the absorber passes through the regenerator riser, disengages, and transfers back to the absorber through the standpipe. Regeneration is conducted with neat air to minimize heat release and limit temperatures to 700°C (1,300°F). The regeneration heat has a negligible effect on the sorbent temperature in the absorber. The regeneration off-gas containing predominantly SO₂ is sent to a sulfator to be absorbed by the excess limestone in the LASH and converted to CaSO₄.

Elutriated particles are disengaged from gas passing through the high efficiency cyclones at the top of the absorber, and some sorbent is also retained by the regeneration outlet gas. The total fines elutriated from the transport desulfurization absorber are predominantly 20 micron particles from the gasifier and the balance being sorbent. These are recovered downstream in the ceramic candle gas filter and are added to the sulfator. Current design practice is to send the fines to a separate combustor, thereby permitting a sulfator design which needs to handle only the larger solids from the gasifier. Loss of sorbent is estimated to be 45 kg/hr (100 lb/hr) per train for 100 to 150 MW equivalent gas flow (air-blown gasifier).

The salient features of the Transport Reactor Desulfurizer are:

- Based on proven commercial technology
- High mass throughput per capital cost
- Efficient conservation of fine particles
- Effective temperature control
- Small physical footprint

4.2.1.3 Other Systems

Fixed Bed Desulfurization -- The fixed bed process was the original concept utilized by METC in developing hot gas desulfurization (HGD) concepts which use regenerable sorbents, such as zinc ferrite or zinc titanate. The process consists of pressurized fixed bed reactors that are alternately absorbing and regenerating. The sorbent is in the form of 5 to 8 mm (3/16 to 5/16 inch) diameter pellets. Mitsubishi (MHI) is developing a honeycomb fixed bed absorber/regenerator which they are testing with a 2 MWe slipstream and appear to be favoring that concept over the fluidized bed. (Modern Power Systems, 4/96)

The developers of hot gas desulfurization processes have moved away from fixed bed reactors, primarily because of difficulty controlling of regeneration temperature profiles, which can result in overheating and sintering of the sorbent.

Fluidized Bed Desulfurization -- The Fluidized Bed Desulfurization Process was developed by METC as an alternative to the fixed-bed HGD reactor. Previous fluid bed reactor designs include the Frodingham Desulphurising Plant at Exeter, and the IHI Hot Gas Desulfurization Process, demonstrated in a 20 MWe pilot plant at Nakoso power station, Japan.

Enviropower's pressurized fluid bed IGCC pilot plant at Tampere, Finland has a maximum power equivalent of 10 MWe for coal and 15 MWe for biomass. The gasifier is based on the U-Gas fluid bed gasifier originally developed by IGT. The pilot plant includes a complete hot gas cleanup train which operates at pressures up to 30 bar (450 psia) and at temperatures up to 650°C (1200°F). Final particle filtration is accomplished utilizing ceramic candle filters.

Fluid bed system allows easier temperature control and more flexibility to operate continuously. Also, by permitting a wider cut of sorbent size limitations, it can utilize fine sorbents more effectively than the fixed or moving beds.

The Japanese continue to operate the pilot plant at Nakoso with iron oxide in the fluidized bed mode at 350°C-450°C (660°F-840°F).

KEMA Netherland B. V. has developed and patented a sorbent and HGD process which features continuous sorbent transport between two bubbling fluidized bed reactors - one absorbing and the other regenerating. Bench scale testing has been conducted, and economic evaluations based on the Shell gasifier at Buggenum are promising. KEMA and Foster Wheeler have signed a cooperative agreement for further process development and commercialization. (Meijer, 1996)

4.2.2 Sorbent Manufacturers

Sorbents which have been developed by METC, RTI, E&A and others and have successfully been tested at bench scale, are then produced in larger batch quantities by one of several sorbent manufacturers for further testing. Production of 2.3 kg (5 lb) batches for bench scale testing and nominally 5,500 kg (12,000 lb) batches for GE pilot plant runs have been reported. The initial fills at Tampa Electric CCT are 50,000 kg (110,000 lbs), and at Pinon Pine, 13,600 (30,000 lbs). Contacts were made with the key sorbent manufactures. The following contacts are the interview comments made by those contacted:

4.2.2.1 United Catalysts, Inc. (Wolfe, 1996)

United Catalysts, Inc. (UCI) is a catalyst and sorbent manufacturer from Louisville, Kentucky which makes its own line of catalysts for petrochemical applications and also does contract manufacturing per clients specifications. UCI has been working with DOE/METC for the past 10 years to produce both lab-scale and commercial scale quantities of HGD sorbents. The sorbents which UCI has produced for the HGD program have included zinc ferrite, zinc titanate, and "zinc-based" sorbents which are proprietary formulations. UCI sees good potential for commercialization of the HGD sorbents for IGCC applications. They don't see the sorbents being price competitive against their line of sulfur guard beds.

UCI (as well as Calsicat) has produced HGD sorbents for RTI, E&A Associates, General Electric, METC, and Phillips Petroleum. UCI is a competitor with Phillips for in-refinery applications, but they have no problem producing Z-Sorb under license to Phillips. Significant test quantities were produced for RTI and METC. UCI enjoys the role of producing sorbents without the responsibility of building systems or conducting performance tests.

4.2.2.2 Contract Materials Processing, Inc. (Albers, 1996)

Contract Materials Processing, Inc., Baltimore, Maryland (CMP) is a small contract manufacturing business which utilizes its own proprietary spray drying process for producing fluid bed sorbents. They produced CMP-107 (similar to ZT-4) for RTI, which was tested at the M. W. Kellogg TRTU in 1995. CMP has also produced nahcolite sorbent for GE to use in the CFB chloride guard at the moving bed pilot plant in Schenectady, New York. CMP recalled that \$3.80/lb formerly estimated for sorbent cost was a reasonable number. That equates to \$8,000 a ton, which is a price for a premium catalyst.

4.2.2.3 Calsicat (Christie, 1996)

Calsicat, Inc., Erie, Pennsylvania, is a division of Mallinckrodt Chemical company which manufactures catalysts and sorbents, either on a licensed or proprietary basis. Calsicat has been

identified as the supplier of Phillips Z-Sorb sorbent for the Piñon Pine transport reactor, but they would not confirm or deny it. They have about 150 private clients, and did not reveal details of their business.

4.2.2.4 Intercat, Inc.

Intercat, Inc., Savannah, Georgia is a relatively new manufacturing company that is involved in the production of sorbents for HGD. Intercat has entered into a collaborative teaming agreement with RTI to jointly develop spray-dried zinc titanate sorbents. (Gupta and others, 1996)

4.2.3 Sulfur Fixation

Hot gas desulfurization (HGD) results in sulfur being produced from the regeneration of sorbent as SO_2 , or as CaS from the bottom of the gasifier. In order for the sulfur to be acceptable for landfill or commercial use, the IGCC products must pass through a fixation process that produces elemental sulfur, CaSO_4 , or sulfuric acid.

The sulfur fixation processes discussed in this section have been determined to be the most appropriate processes for disposition of sulfur in the SO_2 -containing regeneration gas. The Direct Sulfur Recovery Process (DSRP), which has elemental sulfur as its final product, has advanced to bench-scale and is included as an alternative recovery process. Also included are two alternative sulfuric acid processes -- the contact process, which requires a dry, high SO_2 -content feed gas; and the wet sulfuric acid (WSA) process, which is designed to convert low-concentration SO_2 in stack gases to commercial grade H_2SO_4 . Since the scope of this study limits the sulfur products to either sulfur or H_2SO_4 , alternative sulfur disposition concepts, such as production of liquid SO_2 , are not included.

Table 4-2 is a summary of the developmental sulfur fixation processes. The table compares the background information, developmental goals and status for the sulfator and DSRP.

Table 4-2
Summary of Sulfur Fixation Process Development Status

<u>PROCESS</u>	SULFATOR	DSRP
<u>DEVELOPER</u>	M. W. Kellogg	RTI/METC
<u>DEVELOPMENT DATES</u>	1991-Present	1988-Present
<u>GOALS</u>	90% Conversion with minimal SO ₂ release from stack	Single Stage Reactor for Near 100% Conversion
<u>PRODUCT</u>	CaSO ₄	Elemental Sulfur
<u>STATUS</u>	Bench Scale 50% Conversion	Tested at METC Modular Gas Cleanup Rig 99.7% Conversion
<u>FUTURE</u>	Demonstration at Piñon Pine CCT Project	Slip Stream Test at 6 fold gas throughput

4.3 Test Results at HTHP Conditions

Recognizing that effective sorbents are critical to the commercial demonstration of hot gas desulfurization, METC is sponsoring the development and testing of regenerable sorbents both in-house at METC, and through contracted efforts. METC has placed its highest priority on the successful demonstration of hot gas desulfurization at the Pinon Pine and Tampa Electric CCT projects. As a means of achieving these goals, METC is sponsoring sorbent development through several contractors, such as Research Triangle Institute, as well as in-house efforts. METC evaluates the performance and suitability of sorbents as a benchmark for further development and ultimate manufacture and demonstration.

The research conducted by METC and its contractors has been aimed at not only maximizing absorptive efficiency, but also at the material science of retaining the initial properties of the sorbent to minimize the sorbent replacement rate. One major key to hot gas desulfurization is the requirement of an attrition-resistant sorbent for economical operation. DOE's Hot Gas Desulfurization Program (Kellogg, 1995) is based on certain sorbent requirements:

- Regenerability - the primary goal,
- Ability to withstand alternate reductive/oxidative cycles,
- Ability to withstand highly reductive gas atmospheres,

- Absorption at temperatures between 538 and 760°C (1000 to 1500°F),
- Absorption pressures between 20 and 40 bar (300 to 600 psia),
- Ability to separate small volume percentage of H₂S (less than 0.5%) from fuel gas,
- Ability to reduce H₂S emission levels to 50-100 ppm,
- Regeneration at temperatures between 482 and 780°C (900 to 1450°F),
- Ability to recover reactivity and resist attrition, and
- Long life at low costs.

Recent research activity includes development of sorbents capable of effectively absorbing H₂S at temperatures as low as 350°C (660°F) and initiating regeneration reactions below 540°C (1,000°F).

The DOE desulfurization test program is composed of three major components: bench scale research, pilot-plant operation, and demonstration as part of the Clean Coal Technology projects. Of foremost concern is the mechanical integrity of the sorbent, which is dependent on the reactor configuration and process chemistry. The sorbent must be resistant to attrition, spalling, and the deleterious effects of steam content in the oxidative regeneration gases. Participating in bench-scale research include the General Electric Corporation (GE) Research and Development Center, Research Triangle Institute (RTI), DOE/METC, Hampton University, Illinois Clean Coal Institute (ICCI), and others.

Providing pilot-plant moving bed facilities are GE Corporate Research and Development Center, Schenectady, New York (Moving Bed) and in-house facilities at DOE Morgantown Energy Technology Center (METC). The METC hot gas desulfurizer PDU is under construction and will have dual capability for examining both fluidized and transport reactor modes of operation.

Companies that are assisting in optimizing manufacturing techniques are Calsicat Corporation of Erie, Pennsylvania, Contract Materials Processing of Baltimore, Maryland, Intercat Corporation of Savannah, Georgia, Phillips Petroleum of Bartlesville, Oklahoma and United Catalysts of Louisville, Kentucky. Other catalyst manufacturers have shown interest and possess additional capabilities.

On-going DOE-sponsored research in desulfurization will involve projects in Advanced Sulfur Control Concepts and Advanced Sorbent Development. The goal of the sulfur control project is to

develop simpler and economically superior processing concepts of regenerable sorbents and to produce by-product elemental sulfur.

4.3.1 Summary of Development and Test Work, Desulfurization Sorbents

Development of a suitable regenerable sorbent for hot gas desulfurization is a major goal in the hot gas cleanup program for IGCC since many of the sorbents developed over the past 20 years have lacked the ability to retain both reactivity and physical integrity following repeated sulfidation and regeneration cycles.

Sorbent development is classified as being geared toward fixed/moving bed and fluidized/transport reactor bed. The main difference between these classifications is the sorbent particle size - fixed bed being pelletized to cylindrical or spherical shapes 3 mm (.12 inch) diameter x 4 mm (.16 inch) long for cylindrical pellets, and fluidized bed being 70-180 micron scale, either granular or spray dried.

METC doesn't consider newly developed sorbents to be viable until they are subjected to 50 sulfidation and regeneration cycles in a bench-scale reactor. Tests can be conducted by the developer at their own facility or at shared bench-scale test facilities such as METC, RTI, IGT, GE or M. W. Kellogg. They generally begin with 10 cycle tests to determine if a sorbent warrants proceeding with a 50 cycle test.

Bench scale tests are conducted in either a fixed, fluid, or transport reactor mode. Following the 50 cycle evaluation, the sorbent can then proceed to larger quantity testing at either the GE moving bed pilot plant in Schenectady, New York, the TRTU at M. W. Kellogg Houston, Texas facility, or at a fluidized bed facility. Recently, there has been a disruption in the fluidized bed PDU operations schedule in that the Enviropower fluidized bed test facility is no longer available to DOE. (Gangwal and others, 1995) With the cost reduction potential of transport or fluidized bed reactors, fluidized sorbent test capabilities are being advanced at METC. These include proceeding with the construction and 1997 startup of the fluidized bed/transport reactor PDU, and operation of the METC riser reactor in a transport reactor mode. METC continues to support both moving bed and fluidized bed sorbents at the bench scale; however, in-house development work is leaning toward fluidized bed and transport reactor sorbents. Initial screening testing varies with the sorbent developers before proceeding to the 50-cycle test. These can include fixed and fluid bed tests, at low and high pressure, primarily to gain insight to sorbent performance and properties at minimum cost.

Following is a description of the development activity currently being conducted on sorbents.

4.3.1.1 U.S. DOE Morgantown Energy Technology Center

The purpose of METC in-house development of hot gas desulfurization sorbents is to make improved sorbents available for use in Tampa Electric and Pinon Pine CCT projects and future plants. (Cicero, 1995) Since the late 1970's, various formulations of zinc-based mixed metal oxides such as zinc ferrite and zinc titanate, have been studied under the sponsorship of METC. Development of the zinc ferrite formulations was discontinued in the early 1990's for various reasons, the primary one being the lack of structural integrity through a series of hot cycles. Tests conducted at the GE Moving Bed test facility resulted in high attrition rates for the zinc ferrite. With zinc ferrite, excessive sorbent loss was observed at a sulfidation temperature of 625°C (1,157°F). Attrition was mainly due to spalling caused by increased molar volume of sulfide and particularly sulfate, in comparison to the metal oxides. This was reported by RTI in 1991 and 1992 at the Annual METC Contractor's Conference.

With the phasing out of zinc ferrite, METC's in-house scientists have concentrated on advanced zinc-based sorbents. METC's approach is to develop a series of sorbents containing about 50 percent zinc oxide. The balance of material in the experimental sorbents has not been revealed by METC. (Siriwardane, 1996 a, 1996 b)

Since 1993, METC has prepared 10 sorbent formulations, classified as METC1 through METC10. Table 4-3 shows the experimental activity surrounding each of the METC sorbents (Siriwardane and others, 1994).

METC high pressure testing is conducted at 20 bar (300 psia) in a bench scale fixed bed hot gas desulfurization unit with a 5.6 cm (2.2 inch) I. D. reactor. The reactor is constructed of Incoloy 800HT. During typical testing, a 16 inch deep fixed bed of sorbent is subjected to alternating periods of sulfidation and regeneration. Sulfidation is accomplished by feeding simulated fuel gas in a down-flow mode at 550°C (1022°F). Regeneration is performed up-flow using air with nitrogen or steam to limit the regeneration exotherm. The feed gas contains 20,000 ppmv H₂S with an hourly space velocity of 2,000/hr.

METC is currently in the process of constructing a Fluidized Bed/Transport Reactor Process Development Unit (PDU) to support METC strategic plans for IGCC, PFBC and Advanced Turbine System (ATS). The PDU consists of a transport reactor/fluidized bed absorber and regenerator, and a transport reactor/fluidized bed absorber and regenerator. The system has capabilities of operating in a variety of modes. Fuel gas is produced from natural gas and SO₂ in a syngas generator, equivalent to 2 to 3 MWe. Operating pressure is 27 bar (400 psia), 400 to

650°C (800 to 1200°F), and regeneration capability at 750°C (1400°F). The PDU is scheduled for operation in late-1997. (McMillian and Bissett, 1996; McMillian, 1996; Bissett, 1996)

METC also has available for testing a 9 mm (.334 inch) I. D. riser tube reactor which operates as a transport reactor. The riser tube is 9 meters (30 feet) high, and operates in a non-regenerable mode with 75 to 150 micron sorbent particles. Capabilities exist for operation up to 800°C (1500°F), 40 bar (600 psia), and sorbent feed of 5 kg (10 lb) per hour. Fuel gas is mixed from bottled supplies, however coal gas from the METC fluid bed gasifier will be available in Mid-1996 for a limited time. (Rockey, 1996) (Shoemaker, 1996)

The history of METC 10 development through its 200-hour test at the GE moving bed pilot plant was reported at the 1996 Coal-Fired Power Systems '96 Review Meeting (Siriwardane 1996). METC 10 sorbent was tested in a low pressure (1.6 bar/23 psig) fixed bed reactor at 540°C (1,000°F) with simulated KRW coal gas. There were no appreciable changes in reactivity during 3.5 cycles and physical deterioration was not observed. METC 10 sorbent pellets, prepared by UCI were then exposed to the 50-cycle bench-scale test with positive results which met all criteria as a possible sorbent for the Tampa Electric CCT project. United Catalysts prepared sufficient material (6,400 kg [14,000 lb]) to go through a 200-hour test at the GE Moving Bed PDU in March 1996. METC 10 sorbent performed well during the GE moving bed operation. Sufficient reactivity was retained in the sorbent after 200-hours of operation, and attrition was 0.45%. METC 10 satisfied the GE requirement for the Tampa Electric CCT project of 6 lbs/cu.ft. of sorbent and less than 0.5% attrition.

4.3.1.2 Research Triangle Institute (RTI)

RTI is developing zinc titanate sorbents for fluidized bed hot gas desulfurization (HGD), utilizing two different techniques - granulation and spray drying. (Gupta, 1996 b) RTI is under contract with METC to determine the feasibility of manufacturing highly reactive, attrition resistant zinc titanate sorbents. The objectives of this project are to identify and demonstrate methods for enhancing long-term chemical reactivity and attrition resistance of zinc oxide-based mixed metal oxide sorbents for hot gas desulfurization. Specific objectives include investigating various manufacturing methods to produce desulfurization sorbents in a particle size range of 50 to 250 microns. (Cicero, 1995)

RTI in-house testing is conducted in a bench-scale fluidized bed sorbent test facility (Gupta and Gangwal, 1993). It is a skid-mounted system capable of operation at up to 870°C (1600°F) at 20 bar (300 psia). The reactor is constructed of a 10 cm (4 inch) schedule 160 316 stainless steel pipe.

The main components of the system are the gas delivery system, reactor assembly, data acquisition and process control, gas analysis system, and off-gas venting system. Sorbent tested in the test rig varies in particle size range from 40 to 300 microns.

Table 4-3
METC Sorbents

<u>Sorbent Identifier</u>	<u>Test Conducted</u>	<u>Significant Results</u>
METC1	Test 10 cycles in low pressure unit	No spalling Lower strength
METC2	Tested in low and high pressure reactors; Designed for fixed bed; 20 cycles tested	No spalling, steam resistant; excellent chemical and physical durability
METC3	Not tested	-
METC4	Test 5 cycles in low pressure unit	Good reactivity, physical durability
METC5	Test 5 cycles in low pressure unit	Decrease in reactivity, good physical durability
METC6	Tested in low and high pressure reactors; 20 HP cycles; Designed for fluid bed; but tested in fixed bed configuration	Chemically stable through 20 cycles; not affected adversely by steam regeneration Good physical durability
METC7	Low pressure tested; 5 LP sulfidations; Designed for fixed bed; -	Chemically stable through 20 cycles; not affected adversely by steam regeneration Good physical durability
METC8	Test 5 cycles in low pressure unit	Decrease in reactivity, good physical durability
METC9	Designed for Fixed/Moving bed; Tested for 50 cycles at high pressure; First commercial preparation	Good reactivity; Some decrease in reactivity during first 5 cycles, but stabilized; physical durability was good
METC10	Also designed for Fixed/Moving bed; Completed 50 cycle test	Completed 200 hour PDU test at GE in March 1996 Good reactivity and physical durability

Granular Zinc Titanate Development

RTI had developed a granulating technique for zinc ferrite which was also utilized for zinc titanate to develop formulations in the 50 to 400 micron range. Of the various formulations, sorbent classified as ZT-4 was determined by RTI to have the best overall performance, and was selected in 1993 for a 100 cycle test to be conducted at RTI. During bench scale testing, it was demonstrated that sulfided sorbent can be completely regenerated with 1 to 5 percent oxygen in nitrogen, and sulfate formation was found to not occur at 750°C and 15 bar (1400°F and 220 psia). The ZT-4 life cycle test was carried out with a simulated Texaco gas containing 11,400 ppm H₂S at 750°C and 15 bar (1400°F and 220 psia). Regeneration was conducted with 2 to 2.5 percent oxygen in nitrogen at 700 to 750°C (1300 to 1400°F). In the fluidized reactor, superficial gas residence time was about 1.24 seconds. Results of the 100-cycle test of the ZT-4 were encouraging. The sorbent consistently reduced H₂S levels down to <20 ppm, with full regeneration. Sorbent capacity ranged from 12.6 wt% in the first cycle to 5.8 wt% at cycle 100, with most of the decline in the first 50 cycles. Sorbent attrition loss was less than 2 percent.

In 1993, RTI executed a sub-contract with Contract Materials Processing, Inc. of Baltimore, MD (CMP) to commercialize the manufacture of granular ZT-4 and produce 3000 kg (3 tons) of ZT-4. RTI arranged for United Catalysts to manufacture 2000 kg (2 tons) of T-2551, redesignated as UCI-5, for shipment in March 1994 to Enviropower in Finland for test. T-2551 is chemically identical to ZT-4, but has lower sulfur capacity. In March 1994, ZT-4 from CMP was sent to Enviropower for testing in the 10 MWe fluidized bed pilot reactor. Average particle size was about 200 microns.

Enviropower's pressurized fluid bed IGCC pilot plant has a maximum power equivalent of 10 MWe for coal and 15 MWe for biomass. The gasifier is based on the U-Gas fluid bed gasifier originally developed by the Institute of Gas Technology (IGT). The pilot plant includes a complete hot gas cleanup train which operates at pressures up to 30 bar (450 psia) and at temperatures up to 650°C (1200°F). Enviropower's IGCC hot gas cleanup concept is based on in-situ sulfur removal using limestone or dolomite and the balance removed externally in two fluid bed reactors using a regenerable sorbent such as zinc titanate. Final particle filtration is accomplished utilizing ceramic candle filters.

UCI-5 was tested in May and September, and ZT-4 was tested in November 1994. Tests were conducted at 20 bar (300 psia) and 500°C (950°F) absorption and 600°C (1100°F) regeneration, the last UCI test and the ZT-4 test being 10 days each. Results of the testing produced the following conclusions:

- Several steady-state operating points with absorber and regenerator together were obtained.
- Very high sulfur removal efficiencies were obtained with both sorbents, with H₂S reduction from 550 ppm to less than 40 ppm at 500°C (950°F).
- Regeneration with steam/air and N₂/air worked without problems, resulting in SO₂ exit concentrations of 1 to 3%. There was some sulfate formation, generally attributed to an inability to raise the regeneration temperature due to low sulfur loading.
- There is some concern regarding the fines generation from both sorbents. The ZT-4 as received contained up to 30 percent fines, which were elutriated from the bed during cold startup tests.

ZT-4 was also sent overseas to be tested in Spain and Gr. Britain. The CIEMAT program in Spain has an objective of investigating H₂S removal sorbents under different operating conditions for coal derived gas applications (Otero, 1995). They are testing sorbents in fixed and fluid bed reactors over a temperature range of 400-700°C (750-1300°F) and pressures of 10-30 bar (150-450 psia). The primary gasification process of interest to CIEMAT is the ELCOGAS project, a 335 MW IGCC project in Puertollano, Spain. The project is designed for cold gas cleanup, but CIEMAT is interested in the potential utilization of hot cleanup if warranted. Tests are in progress, with preliminary results reported (Otero, 1995). Of three absorption/regeneration cycles with ELCOGAS simulated gas, sorbent capacity of from 7.1 to 14.9 percent was reached. Tests were conducted at 25 bar (375 psia) and from 500 to 600°C (950-1110°F). A batch of ZT-4 was also sent to Coal Technology Development Division, formerly part of British Coal. CTDD conducted somewhat cursory tests, 3 cycles at 500°C (950°F) and 10.5 bar (160 psia). Conclusions based on limited results seemed vague and general. (Fantom, 1996)

Spray Dried Zinc Titanate Development

Following the granulation effort on ZT-4, RTI looked into spray drying processes to manufacture ZT-4. United Catalysts prepared sorbent formulations with and without a silica binder. Those with the binder had good attrition resistance, but poor reactivity. Those without silica binder had reverse properties. RTI also tried a joint effort with Dupont to utilize polysilic acid technology, but was unsuccessful due to the presence of free silica in the sorbent. RTI currently is in a collaborative effort with CMP to develop spray-dried sorbent. CMP produced 14 zinc titanate formulations, resulting in CMP-5. CMP-5 has the most favorable attrition resistant properties while retaining chemical reactivity. Spray-dried particle sizes range from 40 to 150 microns,

typical of commercial FCC catalysts used in the petrochemical industry, and suitable for utilization in the transport reactor desulfurizer. Table 4-4 is a comparison of the ZT-4, and CMP-5.

Table 4-4
Comparison of RTI Sorbents

	<u>ZT-4L</u>	<u>CMP-5</u>
Average Particle Size, microns	180	80
Attrition Resistance	-	-
5 hour loss, %	17	13.4
20 hour loss, %	71	14.2
Surface Area, m ² /g	3.53	2.83
Chemical Composition	-	-
ZnO/TiO ₂ (molar)	1.5	1.5
% Binder	5	5
TGA S-capacity (wt%)	22	22.5

RTI proceeded to conduct further testing of the CMP-5 at a bench scale level. Significance of this is that RTI tested the 80-micron sorbent in a fluid bed reactor. Superficial gas velocity during the tests was 46 mm/s (0.15 ft/sec), while terminal velocity for an 80 micron particle was 91 mm/S (0.3 ft/sec). Typical 10-cycle test runs were conducted on CMP-5 to determine the effect of sulfidation and regeneration on sorbent properties. During these short runs, some performance degradation was noticed following steam regeneration, as well as attrition resistance degradation as determined on the RTI attrition test apparatus.

RTI arranged for CMP to modify their spray drying process to produce a larger sized sorbent, named CMP-107. This batch had a particle size distribution in the 80 to 150 micron range with a average particle size of 165 microns. A 50 kg (100 lb) portion of this batch was tested for 50 cycles in the M. W. Kellogg Transport Reactor Test Unit (TRTU) in mid-1995 (Kellogg, 1995). The TRTU pilot plant was completed in May 1995 to operate either as a dense-phase fluid bed or as an entrained reactor. The lower mixing zone consists of a 3 meter (10 foot) section of 38 mm (1 1/2 inch) schedule 160 pipe. Above the mixing zone is a 10 meter (32 foot) tall riser made of 25 mm (1 inch) schedule 160 pipe. Gas and solids leaving the top of the riser flow through a high efficiency cyclone. The standpipe below the cyclone is a 11 meter (33 foot) tall section of 38 mm

(1 1/2 inch) schedule 160 pipe. A nominal velocity of 4 meter/sec (14 ft/sec) is used during absorption.

Results of the testing over 50 cycles showed that the absorption is very good, with no significant leakage of H_2S . A minimum regeneration temperature of 650°C (1200°F) is required for successful regeneration, and additional oxygen in the regeneration gas does not improve regeneration. M. W. Kellogg conclusions stated that significant attrition was observed, estimated to be 0.00005 to 0.00007 kg (lb) of sorbent lost per kg (lb) of sorbent circulated as compared to the desired attrition of 0.000025 kg/kg (lb/lb) circulated.

Post-test characterization of the CMP-107 sorbent showed that the chemical reactivity and sulfur capacity was retained, but that the attrition resistance of the sorbent deteriorated significantly. (Gupta and others, 1996) Results from the three-hole airjet attrition tester showed an increase for 5-h loss from the initial 5.8% to 63.0%. RTI also reported that they are initiating research to lower light-off temperatures for regeneration of CMP-107 by proprietary additives. Parallel to lowering light-off temperature, RTI has teamed with Intercat, Inc., Savannah, Georgia to improve attrition resistance of spray-dried zinc-base sorbents.

4.3.1.3 E & A Associates

Dr. James H. Swisher, Southern Illinois University, operating E & A Associates as a small business person, is being funded by the Illinois Clean Coal Institute (ICCI) to develop a zinc-based sorbent which has improved properties regarding durability and zinc losses through vaporization (Swisher and others, 1995 a, 1995 b, 1996 a and 1996 b). The research activity was conducted from September 1994 through August 1995. As a material scientist, Dr. Swisher approached the problem by doping the zinc titanate with other metal ions such as Ni, Cu, Cr, Mg, and Al. Of the dopants tested, Cr and Al showed good reactivities, and the Cr showed promise for increasing sulfur capacity of the sorbent. Thirteen formulations containing Cr were prepared, and the most successful formulation operating at 650°C and 725°C (1200°F and 1350°F) contained 1 part Cr to 4 parts Zn. At 725°C , no vaporization of Zn was detected. Testing was conducted in an atmospheric pressure, fixed bed reactor with simulated Texaco coal gas at a 2,000/hr space velocity.

Under a different funding arrangement, Dr. Swisher and Dr. R. P. Gupta of RTI jointly developed a series of sorbents which contain an excess of unreactive TiO_2 , which serves as a structural skeleton for the desulfurizing agent $\text{ZnO}\cdot 2\text{TiO}$. Table 4-5 shows the crush strength comparisons for the formulation, classified as formulation B sintered at 1000°C (1850°F), vs. formulation A sintered at 900°C (1650°F).

Table 4-5
Crush Strength Comparisons

<u>Investigator/Reference</u>	<u>Crush Strength (N/mm)</u>
Formulation A	73
Formulation B	224
Mei, Gasper-Galvin, Everitt, 1993	17
Ayala, Gal, Gupta, 1993	12-32
Grindley, 1990	36

Formulation B was prepared in 100-300 micron particles for 10 cycle fixed bed testing at RTI. Significant results were that the sulfur capacity (or breakthrough time) increased with successive cycles. This is attributed to a change in structure with transformation from oxide to sulfide and back to oxide again with regeneration.

In a conversation with Dr. Swisher (1996), he indicated that United Catalysts had prepared a batch of sorbent, which was tested for 20 cycles at RTI in a fixed bed reactor to determine the sorbent's suitability for use in the moving bed desulfurization system. He also indicated that an additional 5,500 kg (12,000 lbs) will be prepared by United Catalysts for testing by GE at Schenectady.

4.3.1.4 General Electric Environmental Systems, Inc.

GE is looking at desulfurization sorbents from two viewpoints (Ayala and others, 1995, 1996). First, GE has been conducting various tests on zinc-based sorbents to determine if they are suitable for use in the moving bed process. Key objective here is to find a sorbent with minimal attrition. Sorbents which have been tested, primarily for crush strength are Phillips Z-Sorb and zinc titanates developed by RTI and prepared by United Catalysts. Secondly, GE in cooperation with IGT is looking at low temperature sorbents, in the range of 350°C to 500°C (650°F to 1,000°F).

4.3.1.5 Hampton University

Hampton University, Hampton, VA has received a grant from METC to develop hot gas desulfurization sorbents for relatively low temperature applications, around 350°C-550°C (650°F-1000°F) (Cicero, 1995). The initial sorbent development has been conducted jointly with RTI, and

the results are promising because the tests show high capacity relative to RTI ZT-4, by factor of 10, and lower regeneration ignition temperatures in the 550°C (1200°F) range (Jothimurugesan and others, 1995a, 1996a, 1996b, and 1996c). The work is now in the second year into a three year program.

4.3.1.6 Phillips Petroleum Company

Phillips Petroleum Company provided some background on the zinc-based Z-Sorb sorbent (Kubicek, 1996). Z-Sorb has been licensed to two manufacturers to make it in three usage configurations: Fixed Bed; Moving Bed; Fluid Bed. Manufacturers are United Catalysts, Louisville, Kentucky; Calsicat, Erie, Pennsylvania.

Original Z-Sorb was made for fixed bed by Phillips for commercial applications, which is removing H₂S from tail gas systems. It is a ZnO-based regenerable sorbent for capturing H₂S and COS. The ZnO is supported in a porous matrix and contains a nickel oxide promoter. Interestingly, Z-Sorb operates at lower temperatures while retaining its kinetics. Phillips has been working on zinc titanate for 30 years, and has evolved into Z-Sorb. Although Z-Sorb is a commercial offering, there is no sales literature available from Phillips.

Z-Sorb contains nickel, which suppresses the formation of sulfate during regeneration, and permits the initiation of regeneration at low temperatures. Z-Sorb originally is made to operate at lower temperatures around 400°C (750°F) and it has good kinetics at lower temperatures as well as deep sulfur removal.

Z-Sorb does not lose its physical structure with steam. Rather, at exposure to steam at high temperatures, the sorbent loses sulfur capacity. Z-Sorb III has been tested at GE (see above) with results that substantiate the required durability, but experienced significant loss of sorbent capacity following 10 sulfidation/regeneration cycles. Phillips is developing Z-Sorb IV to overcome this problem. The testing reported in 1995 at METC indicated that the Z-Sorb testing in the moving bed had lowered capacity due to formation of steam by combustion of tars carried over from the gasifier. Phillips recommends regeneration at 750°C (1350°F).

Phillips has also prepared a fluidized bed version of Z-Sorb III for testing both at M. W. Kellogg transport reactor test unit, and for a 50 cycle test at RTI, supported by DOE/METC. All development is supported by Phillips resources and they had to develop different manufacturing techniques for fluid bed sorbent manufacture. Tests conducted by RTI and GE CR&D have been supported by DOE/METC. (Khare and others, 1996 a)

A 50-cycle fluidized bed life test was conducted at RTI on a batch of Z-Sorb III with a particulate size range of 100 to 300 microns. The following are significant points from the results of the test (Khare and others, 1995; Gupta and others, 1994) :

- H_2S was reduced consistently from 5,000 ppm to <10 ppmv.
- Sorbent was fully regenerable with 2 percent oxygen in nitrogen
- Sulfur capacity was steady for 10 cycles at 20.2 g(S)/100 g(sorbent), but reduced to 10 g(S)/100 g(sorbent) over 50 cycles.
- Attrition resistance was not significantly changed
- Absorption rate remained constant, regardless of lowered capacity.

Z-Sorb III (moving bed mode) is being purchased for the first filling at Tampa Electric. Both Calsicat and United Catalyst are manufacturing the sorbent for the GE moving bed reactor at Tampa Electric. Z-Sorb III (fluid bed mode) is also being purchased for the first filling at the Pinon Pine transport reactor. (Khare and others, 1996 a)

4.3.1.7 Status of Low temperature Hot Gas Desulfurization Activity

The primary activity associated with lower temperature hot gas desulfurization (LTHGD) consists of developing sorbents which retain a number of properties which are most desirable for removal of H_2S to a low level with reasonable kinetics. The thermodynamic equilibria of many metal oxides significantly improve as temperature decreases, making many metal oxide sorbents suitable for LTHGD in the range of 343°C-538°C (650°F-1000°F). Interestingly, chemical reactivates of the sorbents, expected to decrease with decreasing temperature, are expected to incur better sorbent reactivity after a large number of cycles because of the lower thermal stress and lower sorbent replacement cost. In general, the benefit to be gained by lower temperature application may outweigh the small loss of efficiency due to lower temperature application. Following are developers which are concentrating on LTHGD.

GE/IGT

General Electric Corporate R&D and IGT are collaborating on the development of LTHGD sorbents (General Electric 1995). GE is concentrating on sorbents for use in the moving bed process, and IGT is concentrating on sorbents for fluidized bed applications. In 1995, GE conducted screening tests of zinc titanate, doped with varying percentages of molybdenum to

improve sorbent performance, particularly attrition rate. Four formulations were screened in GE-CR&D's bench scale fixed bed reactor at 5 atm. The results indicated that one formulation (classified as C) exhibited the best combination of attrition resistance and sulfur capacity after 20 cycles, and was recommended for preparation and testing in GE pilot plant Run 8.

IGT has reported (Abbasian and others, 1996 a, 1996 b) that based on work conducted in the past year, three promising sorbents have been developed for the temperature range of 350°C-550°C (662°F-1022°F). The sorbents and sulfur capacity appear to be stable or improving during the first 10 to 15 cycles. They state that the attrition resistance of the sorbents are better than UCI-4169 Zinc Titanate.

Phillips Petroleum Company

Phillips reported in 1995 (Khare and others, 1995) that ZnO based sorbents are effective in desulfurization at temperatures above 315°C (600°F). Fluid bed testing with 4.2 percent H₂S and a temperature of 315°C-370°C (600°F-700°F) the sulfur capacity retains 40 to 50 percent of its value at higher temperatures. Fluid bed testing with 4.2 percent H₂S and a temperature of 315°C-650°C (600°F-1200°F) resulted in sulfur loadings in the range of 2 to 22 percent. The best performance was reported at 427°C (800°F) with a loading that ranged from 14 percent to 8 percent over 700 cycles.

In 1996 (Khare and others, 1996), Phillips reported that the Z-Sorb III had equivalent performance at 315°C (600°F) as at 537°C (1,000°F) when tested at similar space velocities. This was an indicator that the sorbent retained similar activity and the test bed had sufficient capacity to retain the same breakthrough profile for both high and low temperatures.

Japanese Iron Oxide at Lower Temperature

Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) was chosen to develop a hot gas desulfurization process under a contract with Japan Ministry of International Trade and Industry (MITI) through the Coal Mining Research Center (CMRC). After a number of preliminary studies, a pressurized fluidized bed absorber and regenerator was chosen using iron oxide as the sorbent. The SO₂ regenerator gas is processed in a RESOX type direct sulfur recovery reactor to recover elemental sulfur. The RESOX tail gas, which contains considerable residual SO₂, is recycled back to the desulfurization process.

A 40 t/d gasifier and desulfurization pilot plant (the Yubari Pilot Plant) was built by IHI in 1981. As a result of this work, hot gas desulfurization was included into the 200 t/d Entrained Flow Coal

Gasification Combined Cycle pilot plant built by the New Energy and Industrial Technology Development Organization (NEDO) at Nakoso power plant. IHI built the hot gas desulfurization unit for this plant based on the fluidized bed process tested at Yubari.

NEDO and the Engineering Research Association for IGCC Power Systems (IGC Research Association) have developed and have been operating a 200 TPD (12.5 MW_e) pilot plant since 1991. The plant is located at the Nakoso power station at Iwaki City. The gasifier is a Mitsubishi adaptation of the Combustion Engineering air-blown entrained flow gasifier, and the hot gas cleanup system operates at 350°C-450°C (662°F-842°F). The hot gas cleanup systems is composed of two parallel systems, one a granular bed filter and fluidized bed desulfurization system, and the other a ceramic candle filter and fixed bed honeycomb desulfurization system. The honeycomb system appears to utilize excess air to carry the regeneration heat from the reaction to a RESOX-type anthracite reactor for reduction of the SO₂. For the purpose of verifying the performance, reliability and durability of MHI's fixed bed dry gas cleanup technology, a 20 TPD capacity pilot stream was installed next to the 200 TPD gasifier. This pilot facility achieved 765 hours of continuous operation and showed 1-5 mg/Nm³ of dust and 20-50 ppm sulfur content at the outlet. The system can produce either sulfur or gypsum. Adopting the fixed bed gas cleanup, which is compact in size, particulate-free, and water-free contributes to the simplicity and cost of the system.

NEDO has achieved significant operating time on the gasifier and the fluidized bed system. Operational problems associated with the fluidized bed system are not disclosed, but their emphasis on the 20 TPD fixed bed system indicate their preference for design.

The significance of the NEDO operation is that they MHI can now propose a totally coordinated IGCC system called Hercules (High Efficiency and Reliability Coal Utilization with Economy and Simplicity). Hercules features the fixed bed desulfurizer resulting in H₂S output levels of 20-50 ppm.

Summary of Sorbent Development

Table 4-6 lists the hot gas desulfurization sorbents which have been developed to the point of being contenders for demonstration in the Clean Coal Technology IGCC demonstration projects. The primary developers are, METC, RTI, Phillips Petroleum GE, and ICCI. Others such as E&A Associates have shown low attrition, and have gained prominence in the sorbent arena.

Table 4-6
Sorbent Development Status

Reserved for Table 4-6

4.3.2 Summary of Test Work, Sulfur Fixation

The regeneration gas stream resulting from a hot gas desulfurization process contains the sulfur removed from the coal gas as sulfur dioxide (SO₂). For most applications, this gas contains essentially all of the sulfur in the coal. In some gasifier applications, the hot gas desulfurization serves as a polisher, and removes only about 10 percent of the sulfur contained in the high sulfur coal, with most of the coal being captured with a limestone or dolomite sorbent. In Section 4.1 processes for converting SO₂ to stable forms were reviewed, which included the Direct Sulfur Recovery Process (DSRP), the sulfator, and commercial acid plants to produce the alternative sulfur products of elemental sulfur, calcium sulfate, and sulfuric acid respectively.

The testing which is being pursued by the DOE for sulfur fixation is centered around the DSRP process and studies of the oxidation of gasifier LASH for application to sulfator design for use with the KRW and/or transport reactor. The other processes considered for sulfur fixation consist of commercially-available sulfuric acid plants which are not being tested, other than an integration with the slip stream HGD at the Tampa Electric Company CCT site, Lakeland, Florida.

4.3.2.1 Direct Sulfur Recovery Process (DSRP)

In July 1993, RTI, under contract to METC, initiated a program for the Slipstream Testing of the DSRP. The goals of this effort were: 1) to develop an integrated, skid-mounted, bench scale fluid bed desulfurizer (FBD/DSRP) reactor system; 2) to test the integrated system for an extended period with a slipstream of coal gas to quantify degradation in performance, if any; and 3) to design and fabricate a pilot-scale DSRP reactor system capable of operating on a six-fold volume of gas greater than the bench scale system.

The initial testing involved assembling the FBD/DSRP to operate on a slip stream from the METC experimental fluid bed gasifier (Gangwal and others, 1994; Gangwal and others, 1995, Portzer, 1996). The desulfurization section consisted of a fluidized bed absorber/regenerator utilizing ZT-4 zinc titanate. The DSRP consisted of two stages and sulfur condensers and utilized the proprietary RTI catalyst. The system was designed to handle 185 scf/h (4.3 percent of the gasifier flow) particulate-free at 550°C (1000°F) and 25-28 bar (365 to 415 psia). The test rig was assembled in a 15 m by 4 m (50 ft by 12 ft) modified office trailer and placed on the METC site in August 1994. Shakedown was completed in September 1994.

A formal 160-hour slipstream test was begun in October 1994. The test run was shortened to 70 hours due to gasifier operating problems, clogging of the feed line with particulates, and clogging

of the reducing gas feed orifice in the DSRP section. The results, though developed over a brief time period, indicated the following:

- Sulfidation of the ZT-4 sorbent was successful, demonstrating 99+ percent removal of H_2S from the gasifier stream. The ZT-4 was successfully regenerated with 2.5 percent oxygen in nitrogen, showing no sulfate formation.
- Steady-state, totally integrated operation of the DSRP was not possible due to the limited operation time. Three simulated SO_2 tests were conducted on the DSRP, with one of the tests not successful due to plugging of the fuel line orifice. The most significant result was that the DSRP conversion up to 99.7 percent was achieved in a single stage.

Because of the high conversion with a single stage, the DSRP design will be changed from a two stage to a single stage system, with improved economics. Budget priorities have resulted in placing future testing of the METC system on hold. The design for the 6-fold DSRP system has been initiated by RTI, and plans are in place to test the DSRP at the PSDF. The program goal included slip stream testing at the Enviropower gasifier pilot plant at Tampere, Finland under the then-existing CRADA. That CRADA term has expired, resulting in cancellation of the Enviropower testing (Dorchak, 1995).

4.3.2.2 Sulfator Studies

From 1991 to 1994, M. W. Kellogg, under contract to METC, conducted a series of laboratory-scale experiments to characterize the conversion of sulfided calcium-based sorbents to sulfates (Katta and others, 1994). Essentially they were characterizing the design and operating conditions of the sulfator to be utilized with the KRW gasifier or transport reactor with in-situ desulfurization. Following are some of the results from the study:

- For oxidation of LASH/DASH (limestone/dolomite) with air at 900°C ($1,700^\circ\text{F}$), significantly higher oxidation levels were obtained with DASH rather than LASH. The LASH/DASH acronyms refer to a mixture of either limestone or dolomite sorbent remaining in the gasifier ash stream combined with the ash from the coal. There was evidence reported in the literature search that dolomite is less susceptible to sintering at 900°C (1700°F), and does not lose its reactive sites.
- For absorption of SO_2 in the presence of air to oxidize CaS to CaSO_4 , fresh sorbents showed good absorption characteristics. Absorption of SO_2 on LASH and DASH was poor, attributed to pore closure from the high processing temperature. This resulted in a

recommendation that sufficient fresh sorbent be added to the sulfator when processing regeneration gas to prevent SO₂ leakage.

- KRW LASH was tested in the transport reactor test unit (TRTU) to determine the level of oxidation which could be achieved. Operating at 850°C (1600°F), oxidation levels in the range of 50 percent were achieved, with some results as high as 74 percent depending on oxygen concentration and particle size.
- Foster Wheeler DASH when tested in the TRTU resulted in oxidation of 70 to 90 percent. This reinforced the recommendation that dolomite be used as an in-situ sorbent.

4.4 Technical Issues

Hot gas desulfurization (HGD) has been identified by DOE as the means by which the sensible heat of the low heating value fuel gas may be retained, resulting in increased IGCC efficiency, maximum power from the gas turbine, and improved economics. The major issue associated with HGD is the need for the technology to be demonstrated for an extended period at a scale equivalent to commercial operation. Until this is accomplished, IGCC project planners will be driven toward traditional cold gas cleanup. Should an IGCC plant be designed and constructed with hot gas cleanup, the entire heat and material balance of the plant is dependent upon successful operation of the cleanup system, and conversion back to cold gas cleanup is not a practical option.

4.4.1 Hot Gas Desulfurization Sorbents

The key component in a regenerable HGD process is the sorbent. The mixed oxide sorbent is sulfided at 600°C (1100°F), physically transported, and regenerated back to the oxide at up to 750°C (1400°F). In doing so, the sorbent is required to retain its sulfur loading capacity and physical integrity, both criteria which are key issues in sorbent operation. Operating the HGD at lower temperatures places less stress on the sorbent, thereby having the potential for retaining both capacity and physical integrity. (See Section 4.3.1.7) At lower temperatures, additional issues may surface, the primary ones being the feasibility of firing off the regeneration reaction at less than 540°C (1,000°F)

Due to the lower rate of sorbent circulation, attrition is less critical for sorbents utilized in the GE moving bed process than in fluid beds. Sorbent sulfur capacity is less critical with the fluid bed and transport reactors due to the low utilization of sulfur capacity in those processes. Attrition resistance affects the commercialization of fluidized processes because of the continuous activity in the beds.

Another operational problem which has occurred in the development of HGD sorbents is the formation of sulfates during regeneration. Sulfate can be removed by heating the sorbent to 750°C-800°C (1400°F-1500°F), but this approaches the sorbent sintering temperature.

Research objectives are aimed at developing sorbents to resolve these issues. Sorbent formulations are a compromise to meet the operational criteria for an IGCC installation. Phillips Z-Sorb has been tested and found to be attrition resistant and suppresses the formation of sulfates. It has been selected as the initial fill for both Tampa Electric and Piñon Pine Clean Coal Technology projects.

Long term stability of sorbents has yet to be demonstrated. 200 hour testing at the GE PDU is a precursor to its demonstration in a slipstream from the Tampa Electric IGCC project. Long term stability of sorbents will also be demonstrated at the Piñon Pine project which has a transport reactor HGD.

4.4.2 Hot Gas Desulfurization Processes

HGD processes have been evolving since the concept began in the mid 1970's. Evolution of the processes has been tied to an effort to adapt the process to the operating characteristics of the sorbent. Issues affecting HGD processes can be traced back to operation with the regenerable sorbent, that is, sulfur capacity, attrition, and sulfation. Table 4-7 identifies both the issues and attributes that can be associated with the four types of HGD process.

Most significant issues are those associated with the GE moving bed and with the transport reactor since they are the reactors which are being used in the clean coal demonstration projects. A key issue which affect all of the processes is that of not having been demonstrated for an extended duration. This should be resolved at Tampa Electric and Pinon Pine.

4.4.3 Sulfur Fixation Processes

When sulfur is extracted from the IGCC plant, it can be in several forms and concentrations. For KRW or transport reactor, the ash product consists of a LASH, a limestone-ash mixture which contains CaS. For disposal, the CaS must be converted to CaSO_4 by oxidizing the mixture in a sulfator, which is essentially a circulating fluidized bed combustor that converts the CaS while minimizing production of SO_2 . There are several developmental issues associated with sulfators, but the key one is that the viability of the KRW IGCC process is dependent upon the successful implementation of a sulfator. Successful sulfator development is contingent upon 90 percent conversion of the CaS with minimal production of SO_2 . Fines collected from the particulate filters are burned separately in a fines combustor.

The second form of sulfur fixation from an IGCC plant is in the form of a regeneration stream comprised of SO_2 , nitrogen, and trace remnants of oxygen. In the case of IGCC, the Direct Sulfur Recovery Process is being developed to react SO_2 with a stoichiometric amount of fuel gas (CO or H_2) to produce elemental sulfur. Opportunities exist for the production of elemental sulfur from SO_2 streams which are produced from either gasification or combustion processes, such as FGD. Following successful bench scale testing, the DSRP needs to be demonstrated as a steady state process either in a pilot plant or as a slip stream demonstration.

The third concept for sulfur fixation include sulfuric acid production from the SO₂ stream. Although the acid plants are commercial, integration of HGD processes with the acid plants needs to be demonstrated.

Table 4-7
Issues and Attributes of HGD Processes

	ISSUES	ATTRIBUTES
Fixed Bed	Hot valving between vessels Difficult temperature control Complicated regeneration procedures to destroy sulfates Off gas has varying SO ₂ concentration	Low sorbent utilization to prevent H ₂ S breakthrough Permits good gas/solid contact
Moving Bed	Hot isolation valve between absorber and regenerator Process is not less complicated than fixed bed Requires high temperature valving Requires attrition-resistant sorbent for economical operation Heat removal and temperature control require recycle loops	Multi-injection points for regeneration gas to control temperature Permits good gas/solid contact Maintains steady, predictable level of SO ₂ in regeneration off gas (12% for zinc ferrite; 15% for zinc titanate).
Fluidized Bed	Requires provisions for hot sorbent transport Requires Two stages (beds) for efficient performance	Allows easier temperature control and more flexibility Can utilize sorbent fines more effectively than the fixed or moving beds
Transport Reactor	Requires initiation of regeneration at low temperature with low oxygen feed and low sulfur content in sorbent. Has not been operated at commercial scale as HGD process.	Requires only low sulfur capacity utilization Based on proven commercial technology High mass throughput per capital cost Efficient conservation of fine particles Effective temperature control Small physical footprint

4.5 References

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TABLE 4-6 SORBENT DEVELOPMENT STATUS

SORBENT	DEVELOPER	MOLAR RATIO COMPOSITION	APPLICATION	LEVEL OF TESTING	TEST RESULTS	ADDITIONAL TESTING	MANUFACTURER
METC-9	METC	50% ZINC OXIDE	MOVING BED	50 CYCLE HP BENCH SCALE	ACCEPTABLE	NONE PLANNED	UCI
METC-10	METC	50% ZINC OXIDE	MOVING BED	50 CYCLE BENCH SCALE	ACCEPTABLE	200 HR AT GE PDU 3/96	UCI
ZT-4, 180 MICRON	RTI	1.5 ZnO/TiO ₂	FLUIDIZED BED	100 CYCLE AT RTI BENCH SCALE	POSITIVE	CIEMAT-SPAIN; COAL TECHNOLOGY DEVELOPMENT DIVISION, BRITISH COAL	CMP
ZT-4L UCI-5	RTI	1.5 ZnO/TiO ₂	FLUIDIZED BED	5-6 DAYS ENVIROPOWER 10 MWth	POSITIVE	NONE PLANNED	CMP/UCI
CMP-5, 80 MICRON RTI/CMP-107	RTI/CMP	1.5 ZnO/TiO ₂	FLUIDIZED BED	50 CYCLE AT MW KELLOGG TRTU, 1995	ATTRITION LEVEL TOO HIGH	NONE PLANNED	CMP
ICCI-2	E&A ASSOCIATES/RTI	EXCESS TiO ₂ ZnO·2TiO ₂	FIXED BED/ MOVING BED	BENCH SCALE	PRELIMINARY	50 CYCLE AT RTI WAITING FOR MANUFACTURE	UNITED CATALYSTS
Z-SORB III	PHILLIPS PETROLEUM COMPANY	ZINC-BASE PROPRIETARY	FIXED BED/MOVING BED/FLUIDIZED BED/TRANSPORT REACTOR	200 HR TESTING AT GE PDU, 1994 MW KELLOGG TRTU	GE DETERIORATION WITH STEAM REGENERATION ATTRITION RESISTANT /TRTU POSITIVE	FIRST FILL AT TAMPA ELECTRIC CCT SLIPSTREAM FIRST FILL AT SIERRA PACIFIC CCT	CALSICAT AND UNITED CATALYSTS
Z-SORB IV	PHILLIPS PETROLEUM COMPANY	ZINC-BASE PROPRIETARY	FIXED BED/FLUIDIZED BED/MOVING BED	50 CYCLE TEST TO BE SCHEDULED	N/A	ONGOING	TBD

N/A: NOT AVAILABLE

TABLE 4-1 HGD PROCESS DEVELOPMENT STATUS

PROCESS/ DEVELOPER/ CONTRACTOR	DATES OF DEVELOPMENT FOR HGD	OTHER APPLICATIONS	OPERATIONAL ISSUES	LEVEL OF TESTING	FACILITIES AVAILABLE FOR TESTING	PLANNED DEMONSTRATION
FIXED BED/ METC	1985-1990	CPI CATALYST BEDS	HIGH TEMPERATURE VALVING IN-BED TEMPERATURE CONTROL PLUGGING FROM FINES RETENTION	BENCH-SCALE AT METC WALTZ MILL PDU	BENCH-SCALE AT RTI, IGT, GE, METC	NONE
MOVING BED/ GEESI/METC	1990-PRESENT	PETC CuO PROCESS	HIGH TEMPERATURE VALVING IN-BED TEMPERATURE CONTROL PLUGGING FROM FINES RETENTION SORBENT ATTRITION	3 MW _e PDU AT GE CR&D 1990 TO PRESENT	BENCH-SCALE AND PDU AT GE CR&D	10 PERCENT SLIPSTREAM (25 MW _e) SCHEDULED AT TAMPA ELECTRIC POWER CCT
FLUIDIZED BED METC	1988-PRESENT	PROCESS REACTORS REQUIRING PRECISE TEMPERATURE CONTROL	SORBENT ATTRITION FLUIDIZING VELOCITY CONVERSION EFFICIENCY	BENCH SCALE AT METC AND RTI ENVIROPOWER CRADA	BENCH SCALE AT RTI METC PDU IGT	NONE
FLUIDIZED BED/IHI	1981-PRESENT	NONE IDENTIFIED	OPERATES ON IRON OXIDE AT 427-482C (800-900F)	4 MW _e PILOT PLANT 20 MW _e NEDO DEMO.	4 MW _e PILOT PLANT	20 MW _e NEDO DEMO.
TRANSPORT REACTOR/ M. W. KELLOGG	1992-PRESENT	TECHNOLOGY BASED ON MANY YEARS OF COMMERCIAL OPERATION WITH FLUIDIZED CATALYTIC CRACKER BY M. W. KELLOGG	SORBENT ATTRITION DUE TO FAST BED CIRCULATION LOW TEMP REGENERATION	BENCH-SCALE TESTING AT METC AND M. W. KELLOGG TRTU	METC PDU METC RISER KELLOGG TRTU	95 MW _e FULL SCALE DEMONSTRATION PLANNED AT PINON PINE

5.0 STATUS OF THE TECHNOLOGY - TRACE CONTAMINANT REMOVAL SYSTEMS

A number of trace and minor species including alkali metals, chlorides, nitrogen compounds and hazardous air pollutants (HAPs) may require control either for process reasons or to ensure that environmental standards are met. Interest in the formation and control of HAPs in IGCC and PFBC systems is just beginning. Research to date has been aimed at defining a HAPs emission data base and documenting the effectiveness of present control technologies in reducing HAPs emissions. At present, mercury is the HAP emission of greatest concern and is the only HAP likely to be recommended for control from power plants emissions.

Sodium and potassium compounds formed during coal gasification and combustion can cause severe corrosion in the gas turbine. The alkali problem in IGCC systems is not as severe as in PFBC systems because of the lower gas filtration temperatures in IGCC systems. Indeed, the use of sodium sorbents for the capture of chlorides as NaCl has been successfully tested as an IGCC hot gas cleanup treatment (Bevan and others, 1995). Gas turbine specification for alkali-metal compounds in the combustion gas entering a turbine is equivalent to 0.024 ppm wt (Na+K) (Peterson and Lucke, 1979). A target concentration of 0.07 to 0.1 ppm wt total sodium and potassium in the IGCC fuel gas has been used based on this specification (US/DOE/METC-86-6038). Calculations suggest that, if the aerosol alkali particulate could be removed in PFBC, the residual alkali vapor in the flue gas would be less than this limit (Scandrett and others, 1984).

Most of the chloride present in coal is released during gasification or combustion as HCl. While HCl is listed as a HAP, HCl emissions from power plants have not been determined to be a health hazard (Hansen, 1995) and thus are not likely to be controlled. The effect of impurity HCl in fuel or flue gas feed for gas turbines is not well defined, and currently no concentration limit standard exists. The primary concern for IGCC power plants is the formation of chloride compounds and, if they build up in recycle loops such as in the GE desulfurization process (Bevan and others, 1994), their subsequent deposit on syngas coolers and heat exchangers. The effect of impurity HCl in the fuel gas feed for other power generation systems such as fuel cells is a concern.

A portion of the fuel-bound nitrogen (FBN) in coal is converted during gasification into NH_3 and a lesser quantity of HCN. Some of the NH_3 is subject to conversion to NO_x in the downstream gas turbine so that ammonia removal may be necessary to meet stringent NO_x emission limits or for certain gasifiers that produce high levels of NH_3 . Catalytic decomposition of NH_3 has been studied and tested but is not now commercially available (Krishnan and others, 1988). In addition, some constituents of coal gas are known as potential catalyst poisons. A goal has been set of

demonstrating 90 percent or greater catalytic ammonia decomposition to achieve the one-tenth NSPS emission target for IGCC system configurations. .

This section will review the status of the technology for trace and minor contaminant removal, including process developments and test results at high-temperature, high-pressure conditions.

5.1 Mechanisms of Trace Contaminant Removal at High Temperature and Pressure

The development of advanced power systems is aimed toward the use of gas cleaning temperatures of 370°C to 595°C (700°F to 1100°F) for IGCC and 760°C to 870°C (1400°F to 1600°F) for PFBC. Trace contaminants that form compounds that condense at these temperatures can be captured by efficient particulate removal devices. At the lower temperatures of IGCC filtration, it is possible that these contaminants will be controlled by simply filtering the gases. However, development of removal systems based on other mechanisms has been considered prudent, especially for the higher filtration temperatures of PFBC, should filtering alone prove insufficient to ensure that environmental and process constraints are met. In addition to condensation and filtration mechanisms being investigated, other methods including the use of sorbents and catalytic decomposition are also being studied and tested since certain trace contaminants, including mercury, will not condense and be removed by filtration.

5.1.1 Contaminant Control using Condensation and Filtration

Trace contaminants are removed in power systems by forming compounds that condense and are filtered by efficient particulate control devices. Measurements of alkali vapors made by the British Coal Research Establishment (Fantom, 1993) are much lower than the saturated vapor concentrations, indicating that condensation processes other than vapor pressure condensation are taking place to reduce the equilibrium vapor pressure. These processes include:

- Homogenous Condensation - This occurs when the vapor pressure exceeds a supersaturation concentration. In a particle-free environment this value can be larger than the saturation value. However, in gas cleaning trains with high particulate loadings, seeding will occur preventing a supersaturated gas.
- Heterogenous Condensation - This occurs normally on the surface of particles or other surfaces where the local concentration just exceeds the saturation concentration. In the gas cleanup train the gas is cooled relatively quickly and then spends a longer period of time in the filter vessel allowing the approach to equilibrium.

- Vapor Deposition - This arises when vapor in a hot gas comes in contact with a cool surface. Vapor is either adsorbed on the surface, rapidly exceeding the saturated vapor pressure and forming a condensate, or condenses and deposits as a condensate. Vapor deposition is possible in places such as heat exchanger surface areas.
- Reaction with Ash Components - Alkali vapor levels are probably controlled by ash/alkali reactions in the gasifier/combustor bed since the measured values are below saturation concentrations. Sodium and potassium react to form aluminosilicates. It is impossible to predict accurately the theoretical vapor pressure of alkali above ash components because the exact forms of the aluminosilicates are not known.
- Reaction with Filter Media - Several sources have indicated that alkali vapors could react with the ceramic candle filter media. Chemical attack of aluminosilicates by alkali metal compounds, and silicon carbides by steam and alkali metal compounds appear to pose potential problems due to corrosion and loss of strength. Reactions with silicon carbide granules and the aluminosilicate binder have been postulated (Sawyer and others, 1990).

5.1.2 Contaminant Control using Sorbents

A substantial amount of work has been completed and is ongoing to evaluate alkali and chloride contaminant removal using sorbents over a range of temperatures from 400°C to 955°C (750°F to 1750°F). The mechanisms of contaminant retention have included both adsorption and chemical reaction. Methods of gas/sorbent contacting have included in-bed sorbent injection, sorbent injection prior to filtration, and fixed bed sorption before or after filtration. Another option for contacting gas and sorbent particles is the use of fluidized beds or granular bed filters, either fixed or moving. Application of granular bed filters opens the possibility of collecting both gaseous and solid dust particles in one filter unit.

Alkali sorbents have been primarily clays such as emathlite, bauxite, kaolinite, and fullers earth. All have shown significant removal, with the mechanism reported as either a reaction to produce alkali aluminosilicate compounds or adsorption (Lee and others, 1990; Punjak and Shadman, 1988).

Sodium containing minerals have been evaluated for chloride removal by Krishnan and others (1994). Since the spent sorbent is nonregenerable, research is concentrating on nahcolite, a naturally occurring, inexpensive material that can be disposed of after use.

5.1.3 Contaminant Control using Catalytic Decomposition

The approaches to NH_3 removal which are being developed involve rich-quench-lean combustion processes and catalytic decomposition. Rich-quench-lean combustion processes can be used to minimize NO_x emissions only during combustion, whereas catalytic decomposition can be used to remove NH_3 from the hot coal gas stream before it is used in an application. A catalytic decomposition NH_3 removal system will be necessary for certain gasifier types to meet an IGCC NO_x emission goal of one-tenth NSPS.

Transition metals such as Ru, Ni, Fe, and Co that have moderate metal-nitrogen bond strengths exhibit high catalytic activities for decomposition of NH_3 . Although several studies have examined the catalytic decomposition of NH_3 as related to ammonia synthesis, up until the last decade only a few studies had been performed in hot coal gas atmospheres that contain significant quantities of CO, H_2O , and H_2S , which are known poisons for the commercial ammonia synthesis catalyst (Krishnan and others, 1988).

5.2 Contaminant Removal Test Results

The control or removal of alkali, chloride, ammonia, and hazardous air pollutants is being studied by a number of government and private research institutions both in the U.S. and in the U.K. Highlights of their technical approaches and results to date are discussed in this section.

5.2.1 Alkali Control using Sorbents

Several research organizations have in place programs to evaluate alkali removal using sorbents. In England, the Coal Research Establishment (CRE) has a substantial program in support of their British Coal Topping Cycle Program. In the U.S., programs in support of DOE's Advanced Power Programs have been undertaken by The Energy and Environmental Research Center, Westinghouse Electric Corporation and the Combustion Power Company. In addition, testing of an alkali control device is planned at the Power System Development Facility in Wilsonville, Alabama. Details of these programs are discussed below.

5.2.1.1 Coal Research Establishment (Fantom, 1988)

The CRE of the British Coal Corporation put in place a substantial program to evaluate alkali removal using sorbents over a range of fuel gas temperatures from 600°C to 950°C (1110°F to 1742°F). Options for gas/sorbent contacting included sorbent injection prior to filtration and fixed bed sorption before or after filtration.

Alkali measurements had been made by CRE at 950°C (1742°F) on an atmospheric pressure fluidized bed gasifier. Vapor levels of 1 to 3 ppm wt sodium (Na) and 0.6 to 1.3 ppm wt potassium (K) were measured during many periods of operation with different coals. Alkali removal is required to achieve the target range of 0.07-0.1 ppm wt total alkali in the fuel gas. GE reported (Bevan and others, 1994) that vapor phase measurements in the 450°C (842°F) fuel gas were performed for alkalis at their pilot plant. Preliminary results indicated alkali levels well below the target range, indicating that alkali removal will only be necessary at higher temperatures.

A number of authors have reported development of alkali control technology focused on the use of alkali sorbents in packed-bed reactors. Punkaj and Shadman (1988) used kaolinite, and both demonstrated significant retention of alkali vapors from hot alkali-laden gases. The alkali was shown to react with the clay producing an alkali aluminosilicate compound. Lee and others (1990) used activated bauxite as a sorbent; again significant retention of alkali from hot gases was

demonstrated. The mechanism of alkali retention was by adsorption, and the sorbent could be regenerated by washing out the alkali with water.

A number of potential alkali sorbents were identified by Scandrett and others (1984) and Singh and others (1987) using thermodynamic calculations. These sorbents, including those above, were then screened at Surrey University using a Simultaneous Thermal Analysis (STA) technique (McLaughlin, 1990). The three sorbents discussed above plus fuller's earth (a calcium montmorillinite native to the UK) were then tested on a 0.8-liter reactor installed on a 0.15-m atmospheric pressure fluidized bed gasifier at CRE. The results are summarized in Table 5-1. Each sorbent was sized around 2-4 mm diameter and tested at 950°C (1742°F), with the same fuel gas flow rate.

Table 5-1
Alkali Retention Tests

Sorbent	Sodium ppm wt*		Potassium ppm wt*	
	inlet	outlet	inlet	outlet
Emathlite	1.54	0.25	0.72	0.12
Activated Bauxite	1.26	0.25	0.64	0.17
Kaolinite	1.09	0.19	0.57	0.12
Fuller's Earth	1.26	0.17	0.67	0.06

*averages of 8-20 measurements taken at each location during each test.

Each sorbent showed the capability of reducing the alkali vapor concentrations significantly. Fuller's earth gave the lowest outlet value of 0.17 ppm wt Na and 0.06 ppm wt K. The total value of 0.23 ppm wt is still above the target range of 0.07-1 ppm wt, but is predicted to be lower for a high-pressure system. Work is continuing at CRE to optimize the sorbent process. However, the studies are targeted towards providing an alkali sorbent system for around 600°C (1110°F) application. This technology will only be implemented if cooling of the gas is shown to be insufficient in controlling alkali vapor levels by condensation and filtration.

5.2.1.2 Energy and Environmental Research Center (Mann and others, 1995)

The effort at the Energy & Environmental Research Center, at the University of North Dakota in Grand Forks (UNDEERC), is focused on emission control within the fluidized bed rather than by other hot-gas cleanup techniques. The performance of a fluidized bed is controlled by the chemistry of the bed containing calcium-based sorbents and the gas-solids contact that occurs during combustion of the fuel.

Several of the aluminosilicate minerals (such as kaolin) have the potential to capture alkalis, especially sodium and potassium, under conditions typical of fluid-bed operation of 760°C to 1000 °C (1400°F to 1850°F). The alkalis are adsorbed on the surface and diffuse into the bulk of the alkali getter. In addition, the non-bridging oxygen atoms released when alkalis modify the aluminosilicate mineral structure are potential sites for sulfur capture. The use of a getter to capture alkali in the bed reduces the need for downstream alkali capture devices.

The UNDEERC recently commissioned a 3-in. (75 mm)-ID pressurized fluidized-bed reactor to be used for sorbent characterization, evaluation of gaseous emissions including trace elements, agglomeration, and hot-gas cleanup testing. Initial results from characterization of alkali gettering indicate that in-bed getters can remove a significant amount of the alkali in the bed. Using kaolin as a sorbent, sodium levels in the flue gas were reduced from 3.6 ppm to less than 0.27 ppm. Future work will examine impacts of operating conditions and sorbent type and size on the reduction of alkali.

5.2.1.3 Westinghouse Electric Corporation (Newby and others, 1995)

Westinghouse performed a number of laboratory tests on alkali sorbents to screen candidates and measure kinetics. The objective of the testing was to determine the reaction kinetics and potential performance of emathlite and hectorite, which are calcium montmorillinite clays native to the USA, as alkali sorbents at temperatures from 1000°C to 1150°C (1850°F to 2100°F). This temperature range, much higher than the operating temperatures in either PFBC or IGCC hot gas cleanup systems, was selected for application to advanced, direct coal-fired turbine systems.

Westinghouse concluded from the testing that:

- Both emathlite and hectorite are effective alkali sorbents at temperatures up to at least 1150°C (2100°F).
- The affinities of these sorbents for reaction with NaCl, KCl, and Na₂SO₄ are comparable over this temperature range.
- It is expected that the gas alkali content of the combustion gas will range between 1 and 10 ppmv for a typical bituminous coal over the range of temperatures tested. The acceptable level of alkali in the gas is uncertain, but is expected to range from 20 to 50 ppbv. Roughly 99% alkali removal is required.

- The required emathlite feed rate is estimated to be about 10 times the stoichiometric feed rate to achieve 99% alkali removal. The corresponding emathlite mass feed rate is about 0.5% of the coal feed rate, depending on the specific coal alkali content and the alkali release conditions.

5.2.1.4 Combustion Power Company (Wilson and others, 1996)

Combustion Power Company (CPC) is investigating a non-regenerable filter medium composed of a mixture of limestone and clays such as bauxite, kaolin or emathlite for the control of sulfur and alkali contaminants in coal-derived gas streams. Such a sorbent would also have the potential for the control of halogenated compounds of hydrocarbons; trace metals such as lead, cadmium, and zinc; and tars.

In this concept, the filter medium would be composed of 6-mm chemically reactive spheres, which are the same size as the filter medium used for particulate control. The rate of circulation of the filter medium in the granular bed filter (GBF) for particulate control is on the order of 20 times greater than the rate at which reactive filter medium would need to be added to the filter for multi-contaminant control. Fresh reactive filter medium would be added to the circulating filter medium before it enters the filter. After the filter, spent filter medium would be removed from the circulation loop at the rate at which it is added.

Bench scale tests are used to develop and evaluate multi-contaminant control media. The developed media is evaluated in terms of its chemical and physical properties in a bench-scale environment. The next phase of evaluation will be at the pilot plant scale. Combustion Power Company is participating in the DOE sponsored tests at the Power Systems Development Facility (PSDF) to be installed at Southern Company Services' Clean Coal Research Center in Wilsonville, AL about 40 miles southeast of Birmingham, AL. The first year of testing at the PSDF will be dedicated to the evaluation of the GBF for particulate control. For these tests, the GBF is connected to M. W. Kellogg's transport reactor, which can be operated in either a gasification or combustion mode. After the evaluation of a GBF for particulate control, the opportunity exists to evaluate the GBF with a reactive medium for the control of sulfur and alkali compounds.

The modification necessary to allow GBF testing for multicontaminant removal at the PSDF are relatively straightforward. Lock hoppers will be installed for the addition and removal of multi-contaminant control filter medium. The additional feed and removal systems can be accommodated

within the existing structure. Nine tons of clay/limestone filter medium will be prepared for the test series, which will provide for 80 hours of testing.

5.2.1.5 Power Systems Development Facility (Pinkston and others, 1995)

The Wilsonville Power Systems Development Facility (PSDF) is a joint, cost-shared effort of the United States Department of Energy (DOE), the Electric Power Research Institute (EPRI), M. W. Kellogg, Foster Wheeler USA, Westinghouse, Southern Research Institute, Combustion Power Company, and Industrial Filter and Pump. Its purpose is to address the research and development needs for advanced coal-based power generation systems. Operated by Southern Company Services (SCS), the \$200 million facility will be used to test advanced power system components, evaluate advanced configurations, and assess the integration and control issues of these power systems. Initially the facility will be a resource for long-term testing and performance assessment of hot gas particulate removal in an integrated IGCC and PFBC system environments.

The PSDF consists of several "modules" for component and integrated systems testing, including advanced pressurized fluidized-bed combustion, advanced gasification, particulate control devices, advanced turbine combustors and fuel cells. The APFBC module uses Foster Wheeler's Second-Generation PFBC technology, which employs the partial conversion (carbonization) of coal to a fuel gas, with the remaining "char" burned in a PFB combustor. The advanced gasification module consists of a M. W. Kellogg transport reactor for combustion and gasification of coal. The transport reactor concept is based on Fluid Catalytic Cracking technology, which is used in refineries to upgrade heavy oils. Initially, two particulate control devices (PCDs) supplied by Westinghouse and CPC will be tested on the transport reactor. Operation of a fuel cell using the gases from the transport reactor operating in a gasification mode is also planned in the future.

There are two high-temperature PCDs systems in the APFBC. The carbonizer PCD will be provided by Industrial Filter & Pump (IF&P) and the PFBC PCD will be provided by Westinghouse. Each of these systems consists of three cleaning stages in series - cyclone, a high temperature particulate cleanup device, and an alkali-removal vessel. The systems are designed to control alkali content (total sodium plus potassium vapor phase species) to less than 0.05 ppm wt.

The alkali-removal systems are simple, packed beds of sorbent material contained in vertical, refractory-lined pressure vessels. The sorbent material reacts irreversibly with sodium and potassium vapor-phase compounds at high temperature. Nozzles are provided for gas inlet and outlet at the top and bottom of the vessels respectively, as well as for pellet loading and unloading.

Although the expected alkali content in the circulating PFBC flue gas is lower than turbine tolerance, an alkali getter is being installed in the hot flue gas stream as a safety measure for protection of downstream components (McClung and others, 1995). These pilot plant tests will determine if alkali-removal units are required in future plants.

5.2.2 Chloride Control

Most of the chlorine present in coal is released during gasification or combustion as HCl. The effect of impurity HCl in fuel or flue gas feed for gas turbines is not well defined, and currently no concentration limit standard exists. The primary concern for IGCC power plants are the formation of chloride compounds and, if they build up in recycle loops such as in the GE desulfurization process, their subsequent deposit on syngas coolers and heat exchangers. In addition, HCl vapor in the fuel gas may adversely effect the performance of some hot gas desulfurization sorbents. However, impurity HCl in the fuel gas feed for other advanced power systems such as an integrated gasification fuel cell power plant would definitely be a concern for molten carbonate fuel cells.

Several programs are in place to evaluate chloride control technology. A joint program by SRI, RTI and GE is screening sorbents, testing sorbents in different reactors and updating process economics. GE Environmental Services is testing chloride removal processes in their Hot Gas Cleanup test facility. Also groups are investigating multi-contaminant control, including chloride control, using granular bed filters. Details of these programs are discussed below.

5.2.2.1 SRI International/Research Triangle Institute/GE Corporate Research and Development (Krishnan and others, 1995, 1996a, 1996b)

The primary areas of focus in this joint program are: investigating different processes for fabricating sorbents; testing their suitability for different reactor configurations; obtaining kinetic data; and updating the economics of the process.

HCl is scavenged from industrial and incinerator waste gases by adsorption on activated carbon or alumina, or by reaction with alkali or alkaline earth carbonates or oxides. These sorbents reduce HCl levels to less than 1 ppmv, but they are also relatively expensive and cannot be economically regenerated. Hence, they are not suitable as inexpensive, efficient, and disposable sorbents for chloride removal from hot coal-derived fuel gas streams.

The actual concentration of HCl vapor in a coal gas stream will depend on the chlorine content of the coal, the gasification temperature, and the type of gasifier. Recently, the concentration of HCl

vapor was found to be about 300 ppmv in the gas stream from a fixed-bed gasifier using a coal containing 0.24 wt% Cl (Gal and others, 1994). Bakker and Perkins (1991) noted that the concentration of HCl in gasified coal gas is likely to be about five times greater than that in coal-fired boiler flue gas, because of the lower gas volumes of the coal gas stream.

Bench-scale experiments in the fixed- and fluidized-bed reactors have demonstrated that nahcolite pellets and granules are capable of reducing HCl levels to less than 1 ppm in high temperature coal gas streams at the temperatures between 400°C and 650°C (750°F and 1200°F). Recent experiments focused on experiments at elevated pressures. Fixed-bed reactor experiments with simulated coal gas containing both HCl and H₂S vapor showed similar results as with atmospheric pressure runs.

The sorbents, prepared by pelletizing or spray-drying the natural mineral, have a high capacity of absorbing HCl vapor. A mathematical analysis of HCl breakthrough data and chloride level in the spent sorbents suggest that the rate of HCl uptake by the sorbent is governed by gas-phase diffusion, and it could be described by an overall first-order kinetics. A test in a pilot-scale circulating fluidized-bed reactor at the GE facility established that nahcolite can be used successfully for reducing HCl vapor with high sorbent utilization (Gal and others, 1994).

5.2.2.2 GE Environmental Services, Inc. (Bevan and others, 1995)

The GE Hot Gas Cleanup (HGCU) Program is based on the design and demonstration of the HGCU system in a test facility in Schenectady, New York, at the General Electric Research and Development Center. The facility includes a pilot-scale fixed bed gasifier, HGCU system, a turbine simulator and a rich-quench-lean combustor.

Chlorides in the coal gas cause problems to the HGCU system by adsorbing onto the sorbent in the absorber and being transported to the regenerator, where they are released in the recycle gas. In the recycle gas, the chlorides react with both the sorbent and the SO₂ in the recycle gas to form zinc sulfate and zinc chloride deposits in the recycle loop heat exchangers. This condition causes blockage of the heat exchangers after several days of operation. To prevent this problem, a fuel gas chloride removal system was designed and installed for demonstration in Test 5, completed in November 1993. The chloride removal system consists of a pressurized sodium bicarbonate powder injection system located upstream of the primary cyclone. Sodium bicarbonate powder injected into the hot fuel gas stream at 540°C (1000°F) rapidly calcines to sodium carbonate, forming highly porous particles. The sodium carbonate reacts with the hydrogen chloride in the

coal gas to form solid sodium chloride within the particles. The particles, consisting of unreacted sodium carbonate and sodium chloride, are captured by the primary cyclone.

The pressurized sodium bicarbonate injection system functionally performed as designed, but at reduced efficiency. Based on measurements in the fuel gas stream and a post-test solids analysis, the chloride mass balance around the system indicated that only 35% of the chloride was removed from the gas.

Measurements of the chloride in the recycle loop gas were also performed periodically throughout the test. Chloride levels in the recycle gas were found to range from 1000 to 2000 ppm, as measured in previous tests. Since the plugging of the recycle loop heat exchangers sharply limited test operation of the Process Evaluation Facility (PEF) and represented a significant problem, it was decided to add a chloride "guard bed" to remove chlorides directly from the recycle loop.

A "guard bed" was added to the recycle loop for Test 6, completed in May 1994, to continuously remove chlorides from the recycle gas. The guard bed is a small fixed bed that contains an active volume of approximately 300 pounds of sodium bicarbonate pellets (3-4 mm). Since sodium bicarbonate will react with SO_2 as well as with chlorides, the guard bed was located in the lowest temperature position in the loop, upstream of the recycle compressor. Bench-scale testing of sodium bicarbonate pellets in simulated recycle gas demonstrated that at temperatures between 260 and 290°C (500 to 550°F), reactions with SO_2 are minimized and chloride reactions will proceed rapidly.

A major focus in Test 7B completed in March 1995, was the installation and operation of an enhanced circulating fluidized bed (CFB) chloride removal system. The CFB is designed to replace the in-duct injection of sodium bicarbonate with a system capable of higher levels of removal efficiency upstream of the absorber. The CFB is located downstream of the primary cyclone and provides about a 10-second residence time for the coal gas. Powdered sodium bicarbonate is injected upstream with the coal gas and enters at the bottom of the CFB vessel.

Chloride removal levels were approximately 50-75% at low CFB sorbent bed concentrations and coarser feed stock but increased to over 95% as sorbent inventory was increased to design levels. The CFB was intentionally started at low inventories because of concerns over blockage, then run for up to one hour with the outlet lock hopper closed. Sorbent utilization approached 55% at the conclusion of the test. Chloride levels in the recycle loop were the lowest recorded to date. No fouling of the heat exchangers was observed.

5.2.2.3 Sorption of SO₂ and HCl in Granular Bed Filters

An option for contacting flue-gas and sorbent particles is the use of fluidized beds or granular bed filter either fixed or moving. Application of granular bed filters opens the possibility of collecting both gaseous and solid dust particles in one filter unit. One advantage of using granular bed filters is the long residence time of the sorbents in the system which allows almost complete exploitation of the sorbents and therefore a minimization of the residues.

Sorption of SO₂ and HCl in granular bed filters was studied by Peukert and Löffler (1993) in the temperature range between 400°C to 820°C (750°F to 1500°F). In order to achieve maximal sorbent utilization, pellets were used that were agglomerated from fine limestone powders. Particle diameter of these powders proved to be a key parameter for the achievement of high solid conversions, including solids conversions of over 80% for the sulfation and over 90% for the sorption of HCl. Results of two-component sorption of both SO₂ and HCl showed that sorption of SO₂ is enhanced by the presence of chloride.

Theoretical sorption of HCl can be described with a relatively simple shrinking core model. For the sulfation reaction, however, a more sophisticated pore model, which takes into account the sorbent's internal pore, has to be used. Calculated profiles of solid conversions through reactive beds showed that almost complete sorbent use is possible in counter-current beds.

5.2.3 Ammonia Control

Two approaches to NH₃ removal are being developed: rich-quench-lean (RQL) combustion and catalytic decomposition. RQL combustion techniques are being developed to meet present NO_x emission limits for fuels which contain fuel bound nitrogen. However, combustion processes can be used to minimize NO_x emissions only during combustion, whereas catalytic decomposition can be used to remove NH₃ from the hot coal gas stream before it is used in an application. Moreover, development of an additional NH₃ removal step has been considered prudent for meeting IGCC NO_x emission goals of one-tenth of current NSPS standards. This is especially true since NO_x emission limits are becoming more and more stringent.

Krishnan and others (1988) screened potential NH₃ decompositive catalysts using synthetic coal gas compositions. A number of catalysts were reasonably active at 820°C (1500°F) in a low steam, low H₂S atmosphere. However, the activity decreased at lower temperatures and at higher steam and H₂S concentrations with the exception of one catalyst, HTSR-1. Physical deterioration

was a problem at high temperatures while H₂S poisoning became significant at low temperatures. Continuation of this work and others is described below.

5.2.3.1 Simultaneous Removal of H₂S and NH₃ using Mixed-Metal Oxide Sorbents

This project was a collaborative effort between the Research Triangle Institute (RTI), the prime contractor, and subcontractors SRI International and GE (Gangwal and others, 1993 and 1996). The goal of this project was to reduce plant capital costs by combining two cleanup processes into one reactor. The GE experimental work dealt only with the development of sorbent/catalyst mixtures for moving-bed applications, while the RTI and SRI experimental work focused on the development of sorbent/catalyst mixtures for fluidized-bed applications.

Results from these tests showed that:

- Halder Topsoe, High Temperature Steam Reforming-1 (HTSR-1), a nickel-based catalyst, had a high activity for NH₃ decomposition at 725°C (1340°F) in simulated coal gas streams under low H₂S levels, but also retained high catalytic activities under high H₂S levels.
- HTSR-1 when mixed with a desulfurization sorbent such as zinc titanate could decompose NH₃ effectively until the H₂S level increased as the zinc titanate became fully loaded.
- HTSR-1 continued to exhibit an activity for NH₃ decomposition even after exposure to zinc titanate regeneration conditions.
- MoS₂ had moderate activity for the catalytic decomposition of NH₃. However, its surface area needs to be maintained by addition of suitable stabilizing agents for sustained activity

In an effort to characterize the ammonia decomposition catalyst's activity in a real coal gas stream, METC and RTI tested the Haldor-Topsoe's HTSR-1 in the DSRP mobile reactor laboratory facility on a slip-stream of METC's fluid-bed gasifier. This was the first successful test of an ammonia decomposition catalyst on non-simulated coal gas in the U.S. During the test, the catalyst was exposed contaminants, such as sulfur, chloride, alkalis, and trace species (arsenic, selenium, cerium, etc.) at around 815°C (1500°F) for 120 hours. No visible degradation or deactivation was observed from the impurities in the coal gas.

Data analysis reveals that the raw syngas contained 3000 to 5000 parts-per-million-volume (ppmv) of ammonia and 1300 ppmv hydrogen sulfide, a known nickel catalyst poison. The average ammonia decomposition based on ammonia concentration measurements (inlet and outlet) was 91.9% by impinger sampling and 87.4% by condensate sampling. DOE plans to test the catalyst for longer durations with contaminant laden gas which will include particulates.

5.2.3.2 Advances in Ammonia Removal from Hot Coal Gas

This work was undertaken by Hampton University (Jothimurugesan, 1996a and 1996b) to extend the work of the previous program to fixed bed reactors. The objective of this study was to develop sorbent-catalysts that remain stable for NH_3 decomposition in addition to H_2S removal under cyclic sulfidation-regeneration conditions at pressures up to 20 atm and a temperature of 500-800° C. Zinc oxide-based sorbent-catalysts containing nickel were the primary candidates for this study. A number of sorbent-catalysts were prepared and tested. The best sorbent-catalysts consistently removed 99% or more of the H_2S from a simulated coal gas containing 1 volume % H_2S and were regenerable for multicycle operation at 500°C-700°C (932°F-1292°F). The optimum sorbent-catalyst exhibited significant catalytic activity for NH_3 decomposition at 500°C (932°F) even in presence of 1% H_2S .

Life cycle testing, consisting of 30 cycles of sulfidation, ammonia decomposition and regeneration, was successfully performed on a HART-49 sorbent-catalyst to demonstrate its long-term durability and reactivity. Up to 180 minutes, the sorbent-catalyst showed a very high activity (>90%). The decline in activity after 180 minutes, is mainly due to the poisoning of the catalyst by H_2S . The thirty cycle test showed that HART-49 sorbent-catalyst developed under this project exhibited superior reactivity and regenerability.

5.2.3.3 Catalytic Decomposition of Ammonia in a Fuel Gas at High Temperature and Pressure

Tests were carried out by Enviropower (Mojtahedi and Abbasian, 1995) on the decomposition of ammonia in a simulated gasifier product gas in the temperature range of 700°C-900°C (1290°F-1650°F) using Ni and Ru-based catalysts.

Five catalysts were tested, manufactured by Kemira Metalkat, Finland. The catalysts were in the form of honeycomb monolith, 6.4 cm in diameter and 7.5 cm long, with the porous surface coated with catalytically active metals. They have high specific area, thermal durability, low pressure drop and high activity at high temperatures.

The results obtained indicate that the Ru-based catalyst is more effective than the Ni-based catalysts tested. The activity of the Ni-based catalysts is directly related to their Ni content. An approach to equilibrium ammonia conversion of ~99% can be achieved with these catalysts with a gas residence time of 1-2 s. The activities of the catalysts decreased after about 8 hours of continuous operation, but were restored upon regeneration with oxygen, indicating that the reduction in activity was probably caused by carbon deposition from the fuel gas, covering the active sites on the catalyst surface.

The overall reaction rate appears to have been significantly affected by the gas film diffusion limitation, owing to the low gas velocities used in these experiments. However, the limited amount of non-kinetic data obtained in this study does not allow the rate-controlling mechanisms to be quantified. Therefore the overall ammonia decomposition reaction rate observed in this study is generally a conservative estimate of the actual intrinsic reaction rate, because of the apparent gas film diffusion limitations. Higher reaction rate can be expected under similar operating conditions by increasing the gas velocity through the catalyst while maintaining similar gas residence time.

5.2.3.4 Performance of Low Btu Fuel Gas Turbine Combustors

Since 1990, General Electric Company (GE) has been involved in the development and testing of a turbine simulator and combustion system for low Btu gas turbine fuel (Bevan and others, 1995). GE has designed, constructed, and fired a turbine combustion system simulator with high temperature low Btu fuel. Fuel is supplied by a pilot scale fixed bed gasifier and hot gas desulfurization system located at the GE Corporate Research and Development Center. A rich-quench-lean (RQL) combustor was designed by GE as a low cost, low maintenance gas turbine technology to reduce nitrogen oxide (NO_x) emissions from IGCC/HGCU power generation systems. GE has performed nine fired tests with coal gas from the pilot scale gasifier/HGCU system to evaluate and design optimal fuel nozzle and RQL combustor configurations. Fuel contaminate and particulate compositions were also evaluated during these tests (Feitelberg and others, 1996).

Testing for the full-scale RQL combustor was completed in the gas turbine simulator. Low Btu fuel gas was supplied by the pilot scale fixed bed gasifier and hot gas desulfurization system. Test firing temperatures up to 'F' class gas turbine conditions were achieved, measurement of stability, nitrogen oxide (NO_x) and carbon monoxide were acquired over a wide load range; and metal wall temperature measurements were acquired throughout the combustor. NO_x emissions were lower than expected, with measured levels below 50 ppmv (on a dry, 15% O₂ basis), reaching 5%

conversion of ammonia to NO_x at optimal conditions. Measured CO emissions were between 5 and 30 ppmv (dry, 15% O_2 basis). No damage occurred to any hot gas path components with the combustor liner temperatures and pressure drops close to expectations. The performance of the fuel nozzle, which was designed with results from previous tests, was also acceptable.

5.2.3.5 Development of Topping Combustor for Advanced Concept PFBC

The topping combustor must inhibit the formation of NO_x from syngas that contains fuel-bound nitrogen, have high combustion efficiency, produce an acceptable exhaust temperature pattern, exhibit good stability, and be able to light off at cold plant conditions. The Multi-Annular Swirl Burner (MASB), was chosen as the candidate to meet these requirements (Dowdy and Bachovchin, 1995).

Syngas testing was successfully executed at the University of Tennessee Space Institute, Tullahoma, Tennessee. A stable flame was easily achieved and controlled, without the need for igniter firing. apart from one thin weld crack, without test performance consequence, there was no burner damage. The fuel/air ratio control functioned properly. Rich zone equivalence ratio was controlled in the proper range. There was no flame stretch apparent.

The MASB design will be used at the Power Systems Development Facility (PSDF) in Wilsonville, Alabama, as a topping combustor in the advanced PFBC facility.

5.2.4 Hazardous Air Pollutants

Title III of the Clean Air Act Amendments (CAAA) of 1990, Hazardous Air Pollutants (HAPs), requires the U.S. Environmental Protection Agency (EPA) to establish stationary source categories and to implement regulatory standards for 189 air toxics from source categories emitting 25 tons annually of any combination of HAPs or 10 tons annually of a single HAP. EPA must also issue maximum achievable control technology (MACT) standards. The original list of 189 HAPs may be expanded or reduced based on risk to public health, and once controls are in place, "residual" risk assessments must be performed to determine if there is a need for further reductions. Title III requires the regulation of various source categories on a specific time schedule with electric steam generating units coming in 2000 which is late in the schedule. In addition, Title III also requires that EPA must first study HAP emissions from these sources and report to Congress. An interim report was issued in 1996 with recommendations to follow at a later date. Electric steam generating sources shall not be subject to emission standards pending the findings of the study.

In response to the CAAA of 1990, DOE is participating in a collaborative effort with the Utility Air Regulatory Group (UARG), EPA, and the Electric Power Research Institute (EPRI) to establish an appropriate database upon which future regulatory activities can be based. The field sampling efforts are primarily being led by DOE and EPRI, with a few utility companies generating data for their specific systems.

The Morgantown Energy Technology Center (METC) has funded HAP sampling activities at the Tidd PFBC demonstration site, and the Pittsburgh Energy Technology Center (PETC) at the Louisiana Gasification Technology, Inc. site. METC also funded some limited measurements at the GE gasification and hot gas cleanup test facility in Schenectady, New York. These sites represent advanced combustion and gasification based power system technologies and associated gas stream cleanup systems. In addition, PETC also focused its efforts on establishing a database for a wide variety of conventional coal-fired systems, also representing various conventional and advanced emissions control technologies.

5.2.4.1 Trace Substance Emissions From A Coal-Fired Gasification Plant (Williams and Behrens, 1995)

During the Louisiana Gasification Technology, Inc. (LGTI) demonstration program, the environmental characteristics of some streams, particularly the discharge streams, have been regularly monitored. However, with the passage of the CAAA in 1990, it has become important to define the fate of currently unregulated HAPs from the LGTI process. Most of the HAPs in internal gas streams had not yet been measured at the demonstration facility. The Department of Energy and EPRI developed a program with the assistance of Radian to measure selected HAPs in the discharge streams and in most of the major internal process streams of the LGTI demonstration plant in conjunction with the regular environmental monitoring plan for the plant.

EPA Method 29 is recommended for detecting metals in combustion gas streams, but does not yield accurate results when applied to reducing gas streams. Reference methods do not exist for testing gasification process streams. During this test program, several test methods were used to compare with data from the EPA Method 29 sampling train method.

Results from the testing program indicate that the emissions are extremely low for most metals. Volatile metals such as chlorine and mercury, which were present in the syngas as vapor-phase compounds such as hydrides or carbonyls, are found in the turbine exhaust in about the same concentration as that of a conventional coal-fired power plant.

5.2.4.2 Comparison of HAPs from Advanced and Conventional Power Systems: Tidd versus Cardinal (Erickson and Brekke, 1995)

Trace element partitioning from the Tidd PFBC power plant located in Brilliant, Ohio was compared to the Cardinal pulverized coal-fired plant, which is located adjacent to it. The flue gas ash is measured at the inlet of the hot gas particulate filter (HGPF) for the Tidd Station and at the inlet to the ESP for the Cardinal Station. These two plants burn the same Pittsburgh No. 8 coal making comparisons fairly easy, although there is a significant length of time between the two sampling events over which time the coal samples may vary somewhat. The partitioning that occurs within the power system boiler directly affects the amount of any metal reaching the gas cleanup site and impacts the amount emitted from the total system. For all trace elements except mercury, the PFBC system at Tidd released fewer trace elements into the flue gas stream (entering the HGPF) than the Cardinal Station (entering the ESP). For mercury, both systems released essentially 100% into the flue gas, and none remained with the bottom ash of the systems. Cl, F, and Hg are primarily in the vapor state, and Cu, Mo, Ni, and Se contain greater than 10% of their mass in the vapor state. The remaining elements were primarily present in the ash.

The Tidd system had an HGPF and a downstream ESP. In general, the Tidd HGPF was very effective (99.5%) in collecting the material as it passed through it; however, the higher operating temperatures allow some elements to remain in the vapor state. The HGPF showed a higher collection efficiency than the Tidd ESP for all trace elements except As, Cr, Mo, Ni, and Se. There was an apparent error in the Ni, Cr, and Mo values of the HGPF due to contamination from a sampling probe. This results in a lower calculated collection efficiency for Cr, Ni, and Mo in the Tidd system. The HGPF showed a higher or equivalent collection efficiency than the Cardinal ESP except for Sb, Cr, Co, Hg, Mo, and Ni. Most of the trace elements escaping through the HGPF are in the vapor state, while a significant number escape through the ESP as particulate.

The testing results demonstrate that the plants studied have fairly low emission factors for total CAAA trace elements on average. It is important to note that the amount of trace elements emitted into the atmosphere is largely a function of the amount present in the coal initially. The Tidd HGPF, however, shows a higher Hg emission than the Cardinal ESP; although the amount was small.

5.2.4.3 Assessment of HAPs from Advanced Power Systems (Erickson and Brekke, 1996)

This review of trace element emissions from advanced power systems and hot-gas cleanup systems included data from Tidd Station, General Electric hot-gas cleanup, Louisiana Gasification Technology Incorporated, and the Cool Water plant. Very few other sources of information were located, and those that were contained significantly flawed information that was not of value to this project. In addition to the four demonstration and full-scale systems reviewed, nine conventional systems were also reviewed for comparison with the advanced systems.

The potential for the regulation of advanced power systems is currently being driven by the 1990 CAAA. The CAAA list 189 compounds considered HAPs that must be minimized. The current form of the regulations would allow only 10 tons/year of any single HAP and 25 tons/year of all HAPs combined. Any major source exceeding these limits will be required to apply the maximum achievable control technology to their system to meet the regulations. The advanced systems would be governed under regulations derived from the results of conventional system testing.

The overall emission of trace elements from advanced power systems appears to be equal to or lower than that of conventional systems, on average. All systems fall below a total of 1 ton of emission per year. The only area of concern likely is the emission of mercury from the advanced power systems. Regulation of mercury may be expected because of its environmental and health risks. Informal reports indicate that the EPA believes there is significant mercury contamination of lakes from air deposition and that coal-burning power plants are one of the major sources. Since the Tidd APF and other future advanced technologies will operate at temperatures exceeding conventional technologies, it is anticipated that mercury emissions will be an issue.

5.2.4.4 Mercury Control from Coal Combustion

The results of the field sampling efforts suggest the need for additional control processes in coal-fired utilities to consistently achieve high (>90 percent) Hg removal. The control of Hg emissions through injection of carbon-based materials has been demonstrated in both pilot-scale and full scale testing. (Felsvang and others, 1993) Pilot-scale testing investigated the control of Hg emissions in a baghouse and an ESP. The full-scale work reported was focused on dry scrubbers. The removal of mercury inherent in dry scrubbing in full scale systems ranged as high as 95%. In an eastern U.S. installation, the mercury removal efficiency was further enhanced by activated carbon injection upstream of the spray dryer absorber, resulting in removal efficiencies of greater than 99%. (Benson and others, 1993)

The slipstream study by Chang and others (1993) concluded that injection of activated carbon before a fabric filter is capable of removing Hg. The tests were performed on EPRI's Transportable Pulse-Jet fabric filter pilot plant at the Comanche Station Unit 2 firing a Powder River Basin, low sulfur coal. The results suggested a dependence on the flue gas temperature and the amount of activated carbon used in determining the fraction of Hg removed. For temperatures around 120°C (250 °F), they reported a carbon:Hg weight ratio of 3,000:1 for high Hg removal. Pilot plant studies conducted at UNDEERC employing different coals, however, showed lower Hg removal (60 percent) with activated carbon injection at a similar carbon:Hg weight ratio. (Miller and others, 1995)

Research at Argonne National Laboratory has been focused on techniques to enhance the capture of elemental mercury in existing flue gas cleanup systems (Livengood and others, 1995). For dry processes, these studies included evaluation of the factors that control mercury capture by commercial activated carbons (both with and without chemical pretreatment), testing of novel proprietary sorbents under development by several firms, and investigation of sorbents based upon chemical pretreatment of low-cost mineral substrates. To enhance the ability of wet scrubbers to capture mercury, the studies looked at the effects of improved mass transfer through both mechanical and chemical means, as well as the conversion of elemental mercury into more soluble species that can be easily absorbed.

The research at Acurex included bench-scale experiments to study capture of three species of Hg by different activated carbon sorbents at temperatures and Hg concentrations representative of applications in coal combustors. (Krishnan and others, 1995)

5.3 Technical Issues

Trace contaminants in IGCC and PFBC power systems that may require control for either process reasons or to insure that environmental standards are met include HAPs, alkali metals, chlorides, and ammonia. The issues and R&D needs for each of these are discussed below.

5.3.1 Hazardous Air Pollutants

Preliminary results from HAP emission testing programs for advanced power systems indicate that the emissions are extremely low for most metals. Volatile metals which were present as vapor phase compounds are found in the flue gas exhaust in about the same range as that of conventional coal-fired power plants.

Both DOE and EPRI concluded that the overall health risk posed by inhaling emissions from fossil-fired power plants to be minimal (Allan, 1995). Emissions from 51 different power plants were studied, including 29 coal-fired plants, 13 oil-fired plants, and nine gas-fired plants. The EPA interim report to Congress with its conclusions and recommendations for control measures, if any, was due to be issued on April 15, 1996 but has been delayed. The final report with regulatory determination is scheduled to be issued on December 15, 1996.

While HCl is the largest HAP emission from coal-fired power plants, it has not been determined to be a health hazard and thus is not likely to be controlled. Mercury is the only HAP likely to be controlled. The environmental behavior of mercury and the level of mercury contamination in water has made mercury a matter of concern due to its ability to bioaccumulate in fish. The control of mercury through injection of carbon-based materials has been demonstrated (Felsvang and others, 1993). A number of challenges need to be addressed in the development of mercury control measures for coal-fired systems. These include (Hansen, 1995):

- The low concentration of mercury in the flue gas
- The presence of mercury in the vapor phase
- Multiple mercury species and variable speciation
- The potential interactions of other flue gas species with mercury
- The need to either recover captured mercury or to dispose of it in a stable form
- The extremely low solubility of elemental mercury in flue gas desulfurization systems

If mercury is regulated, a phase-in of the controls is likely. A tentative schedule calls for proposed regulations no later than December 15, 1998, promulgated regulations by December 15, 2000, with a phase-in period to follow.

5.3.2 Alkali Metals

The alkali problem in IGCC systems is not as severe as in PFBC systems because of the lower gas filtration temperature in IGCC systems, 370°C to 595°C (700°F to 1100°F) for IGCC and 760°C to 870°C (1400°F to 1600°F) for PFBC. At IGCC temperatures, alkali should be controlled by condensation and efficient particulate filtration.

At higher PFBC temperatures, measurements have indicated that alkali vapor levels are greater than turbine limits of 0.024 ppm wt (Na+K), (Lee and others, 1993) suggesting that a method to reduce these vapors may be necessary. The greatest concern is with the PFBC carbonizer which combines a higher temperature with a reducing atmosphere. Laboratory tests using clays have successfully reduced alkali vapor concentrations significantly (Newby and others, 1955). Fixed bed alkali getters will be tested at the Wilsonville Power System Development Facility. These tests will determine both the magnitude of the emissions from the carbonizer and PFBC and the ability of the alkali getters to reduce alkali vapor levels.

Several sources have indicated that alkali vapors could react with ceramic candle filter media. A major concern is alkali attack on the binders. Most of the work done with alkali getters used fixed bed reactors located down stream of the particulate filters. Attempts by filter vendors to introduce an alkali getter or a precoat on candle filters were not successful (Seymour, 1966). Additional work may be needed to demonstrate techniques to reduce alkali efficiently upstream of the particulate filters.

A granular bed filter, by controlling both alkali and particulate emissions, addresses this concern. In this concept, the absorbant would be composed of chemically reactive spheres, which are the same size as the filter medium used for particulate control. A CPC granular bed filter will be tested at the Wilsonville Power Systems Development Facility.

5.3.3 Chloride Compounds

Most of the chlorine in coal is released during gasification or combustion as HCl. The effect of impurity HCl in fuel or flue gas feed streams for gas turbines is not well defined, and currently no concentration limit standards exist. Although the highest of the utility emissions of trace contaminants are for HCl, recent assessments indicate that HCl emissions from individual coal

combustion sources are not likely to pose a human health risk (Allan, 1995) and thus are not likely to be controlled. The effect of impurity HCl in the fuel gas feed for other power generation systems such as molten carbonate fuel cells which has a tolerance of less than 1 ppm HCl (Pigeaud and Wilemski, 1992) is a concern.

The primary concerns for IGCC power plants is the formation of chloride compounds and, if they build up in recycle loops such as in the GE desulfurization process, their subsequent deposits on syngas coolers and heat exchangers. In addition, HCl vapor in the fuel gas may adversely effect the performance of some hot gas desulfurization sorbents. Effective chloride removal has been demonstrated in the GE pilot plant using a circulating fluidized bed to inject sodium bicarbonate into the coal gas (Bevan and others, 1995). Slip stream gasification tests are planned in 1996 at the Tampa Electric Company CCT demonstration plant using the same configuration.

5.3.4 Ammonia

The approaches to NH_3 removal which are being developed involve rich quench lean (RQL) combustion and catalytic decomposition. RQL combustion techniques are being developed to meet present NO_x emission limits for fuels which contain fuel bound nitrogen. Catalytic decomposition can be used to remove NH_3 from the hot coal gas stream before it is used in an application. Moreover, development of an additional NH_3 removal step has been considered prudent to meet more stringent NO_x emission regulations from gas turbines which are expected to be reduced from the present level of 25 ppm to 10 ppm or less.

Laboratory work has been continuing on the catalytic decomposition of NH_3 under DOE sponsorship (Gangal and others, 1993). Plans are to continue work to develop innovative and effective techniques for removal of ammonia in coal gas (Staubly, 1995).

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6.0 IMPACT OF HOT GAS CLEANUP ON COST AND PERFORMANCE FOR ADVANCED POWER SYSTEMS

Variations in the cost and performance of hot gas cleanup have impacts on advanced power systems, ultimately affecting their commercialization . The sensitivity of the capital cost, operating cost, and cost of electricity to hot gas cleanup system parameters was determined by starting with baseline plant design and cost figures, adjusting the parameters, and assessing the changes. Additionally, the impact of operating the cleanup systems of the power plants at lower temperatures was assessed. The design and cost estimates of advanced power plants were not within the scope of this task, and therefore IGCC and PFBC plant designs prepared in previous work are utilized as baselines for performance and economic comparisons.

For both IGCC and PFBC plants, two types of impacts were considered: the sensitivity of COE to changes in general plant parameters, such as total plant cost; and the sensitivity of COE to changes in specific HGPU parameters, such as filter face velocity. IGCC plants are impacted by both hot gas desulfurization and hot gas particulate removal, while PFBC plants are only impacted by hot gas particulate removal.

6.1 Impact on IGCC Plants

Two IGCC plants were selected based on 400-MW_e plant conceptual designs prepared previously for DOE/FE (Parsons Power, 1995). These plant designs were selected to represent the wide range of gasifier products and the utilization of desulfurization at 604°C (1,120°F) as either a polisher or as a bulk sulfur remover. The first plant design and cost estimate is based on the KRW air-blown gasifier with in-situ desulfurization and a hot gas desulfurizer. The second plant design and cost estimate is based on the Destec oxygen-blown entrained flow gasifier with a hot gas desulfurizer to remove the bulk of the sulfur. Both IGCC plant designs utilize ceramic candle filters as final particulate control devices before combustion in the gas turbine.

Table 6-1 identifies the parameters that impact operating costs associated with hot gas desulfurization for the baseline IGCC plants. These parameters are the result of empirical data obtained from PDU operations and projected performance characteristics of HGD systems and sorbents.

Table 6-1
IGCC Hot Gas Desulfurization Cost Parameters

Parameter	KRW	Destec
MWe net	397	380
Pressure, inlet, kPa (psia)	2,551 (370)	2,716 (394)
Temperature, inlet, °C (°F)	593 (1,110)	593 (1,100)
Flow, inlet, kg/s (lb/hr) gas	133 (1,053,900)	59 (470,630)
Flow, inlet, m ³ /min (acfm)	937 (33,102)	497 (16,583)
H ₂ S Concentration, inlet	600 ppmv	6000 ppmv
H ₂ S Concentration, outlet	10 ppmv	10 ppmv
Sorbent Inventory, kg (lb)	30,500 (67,200)	45,400 (100,000)
Sorbent Attrition, kg/s (lb/hr)	0.032 (250)	0.066 (520)
Sorbent Cost, \$/lb	3.50	3.50

6.1.1 IGCC Sensitivity to General Parameters

The capital cost of hot gas cleanup systems are between 10 and 15 percent the IGCC total plant cost (TPC). Desulfurizer and particulate filter costs are 11 percent and 4 percent, respectively, of the TPC of a KRW IGCC plant, and 8 percent and 2 percent, respectively, of the TPC of a Destec IGCC plant.

The Cost of Electricity (COE) is a function of Capital Cost, Operating Cost, Capacity Factor, and financing. By determining how each baseline COE varies as a function of percentage changes in capital and operating costs, and absolute value change in capacity factor, curves can be plotted which show the impact on COE for air blown and oxygen blown IGCC. Figures 6-1 through 6-3 show the relative changes in cost of electricity as functions of changes in capital, consumables, and capacity factor parameters for the KRW and Destec plants.

As a general observation, the slope of the COE curve is shallow for the capital changes, indicating that the gas cleanup portion of the capital cost has a relatively minor impact on COE. Similarly, the consumables are a small fraction of the operating costs which, in turn, are less than 20 percent of the COE. As expected, the capacity factor has a major effect on the COE.

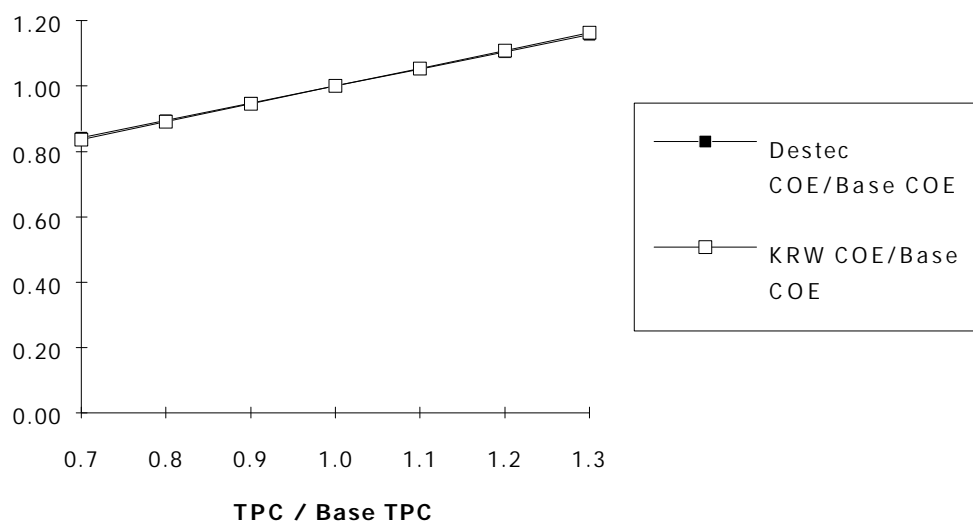


Figure 6-1. IGCC COE Sensitivity to Total Plant Cost

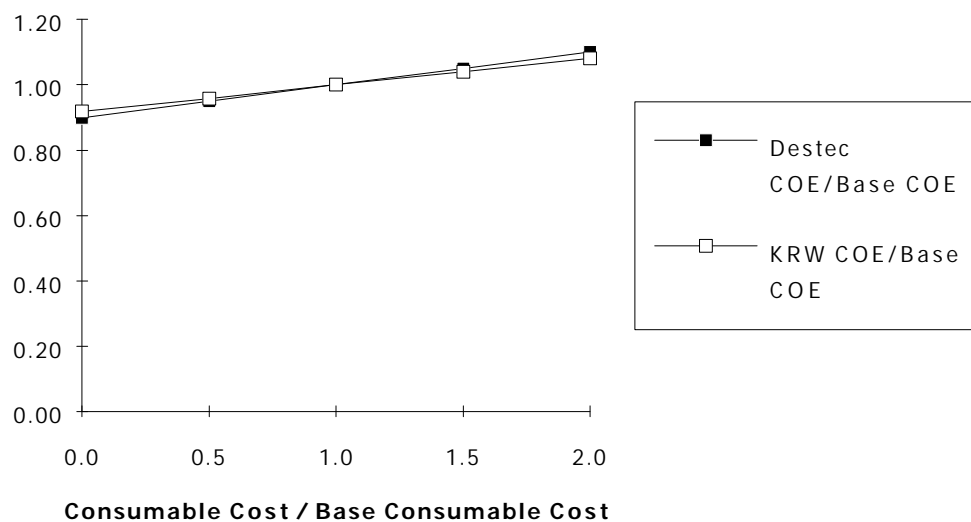


Figure 6-2. IGCC COE Sensitivity to Consumables Cost

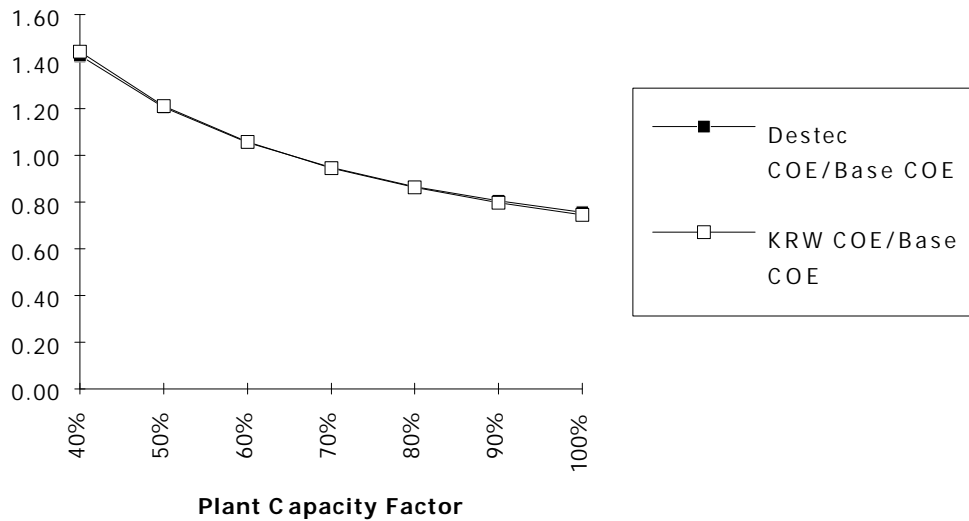


Figure 6-3. IGCC COE Sensitivity to Capacity Factor

6.1.2 IGCC Sensitivity to HGCU Parameters

Table 6-2 shows the causes and effects of sensitive changes in the IGCC plants, and identifies the area and direction of impact. The first column of the table shows the parameter that causes the impact and the second column shows the effect that results from the cause. Table 6-2 is not all-inclusive; rather it provides guidelines for identifying areas of sensitivity.

High temperature HGD can result in increased O&M costs due to increased sorbent attrition and resultant increased sorbent replacement rates. The overall impact of lowering the hot gas desulfurization temperature amounts to increased vessel sizes of the HGD system due to longer gas retention times and, increased throughput of the gasifier with increased variable costs due to lowered efficiency. However, the impact on cost of electricity associated with the HGD system from lowered temperature would probably result in a lowering of cost due to longer sorbent life and lower cost for sorbent replacement.

Table 6-3 shows the effect that varying operating parameters can have on IGCC cost of electricity for the KRW plant (transport reactor HGD) and for the Destec plant (moving bed HGD).

Table 6-2
Effect of Hot Gas Cleanup on IGCC Parameters

<u>CAUSE</u>	<u>EFFECT</u>	<u>IMPACT</u>
PARTICULATE RECOVERY		
Change in face velocity	Change filter area and vessel volume	Increase or Decrease Capital Cost
Change filter material life	Change filter element replacement frequency	Higher or Lower O&M and Capacity Factor
Change in Filter Element Cost	Change in Capital Cost	Higher or Lower Capital Cost
HOT GAS DESULFURIZATION		
Reduction in sulfur removal capabilities of sorbent	Increased sorbent replacement rate	Higher O&M Costs
Change in Sorbent Attrition Rate	Change Sorbent Replacement Rate	Change O&M Costs
Sulfate formation during regeneration	Reduced operating efficiency Increased sorbent replacement rate	Higher O&M Costs
SULFUR RECOVERY		
Reduced Sulfator Conversion Efficiency	Requires alternative equivalent sulfator	Higher Capital Cost
Reduced Sulfur Conversion in DSRP	Requires multiple stages in DSRP	Higher Capital Cost
Low SO ₂ Concentration to Acid Plant	Requires larger acid plant	Higher Capital Cost

Particulate filters also have significant impacts on the hot gas cleanup costs for both the KRW and Destec IGCC plants. Table 6-4 indicates the operating characteristics and the parameters that impact the costs associated with the particulate filters utilized for IGCC. Tables 6-5 shows the effect that changing parameters can have on the KRW and Destec IGCC COE respectively.

Table 6-3
Impact of Gasifier Hot Gas Desulfurization on IGCC COE

Changing parameter	Change to	KRW % Change	Destec % Change
Desulfurizer Capital Cost	0.7 x Base	-2.0%	-1.2%
	1.3 x Base	2.0%	1.2%
Sorbent Attrition	0.5 x Base	-2.0	-4.6
	2.0 x Base	2.0	4.6
Sorbent Cost	0.7 x Base	-1.2	-2.8
	1.3 x Base	1.2	2.8

Table 6-4
Summary of IGCC Particulate Filter Base Parameters

Parameter	KRW	Destec
MWe net	397	380
Pressure, inlet, kPa (psia)	2,482 (360)	2,654 (385)
Temp., inlet, °C (°F)	599 (1,110)	610 (1,130)
Flow, inlet, kg/s (lb/hr) gas	133 (1,053,900)	59 (467,630)
Flow, inlet, m ³ /min (acfm)	963 (34,021)	503 (17,766)
Inlet particulate loading, ppmw	1,500	N/A
Particulate size, microns, D50	1.2	N/A
Particulate loading, kg/s (lbs/hr)	0.186 (1,478)	N/A
Candle filter vessel design		
Outside Diameter, m (ft)	5 (16)	5 (16)
Height, m (ft)	20 (67)	20 (67)
Flow, m ³ /min (acfm) per vessel	482 (17,011)	503 (17,766)
Face velocity, m/s (ft/min)	0.025 (5)	0.025 (5)
Candles per vessel	1,172	1,229
Number of vessels	2	1
Filter Cost, \$/element	\$500	\$500
Filter Life, years	3	3

N/A: Not Available

Table 6-5
Impact of Gasifier Particulate Filters on IGCC COE

Changing parameter	Change to	KRW % Change	Destec % Change
Face Velocity	2.0 x Base	-1.7%	-0.90%
	0.5 x Base	3.1%	1.6%
Filter Life	5 years	-0.3%	-0.2%
	1 year	1.7%	0.9%
Filter Element Cost	0.7 x Base	-0.4%	-0.2%
	1.3 x Base	0.4%	0.2%
Redundant Trains	1 Redundant	3.9%	2.0%

6.1.3 Findings

Attrition resistance of the sorbent is important to the economic viability of IGCC. The unit cost and attrition rate of the zinc-based sorbents have the largest impact on the COE of Destec IGCC, followed by desulfurization cost and candle face velocity. Corresponding sorbent cost and attrition rates are only about half as significant in the KRW design as in the Destec design, primarily due to the unique feature of the KRW gasifier that bulk desulfurization is accomplished inside the gasifier. The external desulfurization is essentially a polishing function.

By contrast, the desulfurization costs in the KRW plant affect the COE almost twice as much as the desulfurization costs in the Destec plant. As the KRW plant utilizes an air-blown gasifier which delivers twice as much gas flow as the oxygen-blown Destec gasifier, the capital cost of the KRW is higher than the Destec plant.

The effects of candle filter life and element cost on the COE of the IGCC plants are an order of magnitude less than the effects of hot gas desulfurization parameters. Except for sorbent cost and attrition rate, the hot gas cleanup parameters in the KRW design affect COE about twice as much as the same parameters in the Destec design.

6.2 Impact on PFBC Plants

The PFBC plant was based on a 535 MW_e PFBC design with a carbonizer being developed by Foster Wheeler. The design includes both a coal carbonizer and a circulating PFBC. The plant design and cost estimates are based on updated work performed by both Foster Wheeler and Gilbert/Commonwealth in 1992 (Gilbert/Commonwealth, 1993). The hot gas cleanup systems associated with the PFBC power plants include only particulate control. There is no hot gas desulfurization associated with the exiting gases, and sulfur control is achieved by dolomite injection into the carbonizer and FBC. The base case sulfur control utilizes dolomite sorbent injection in the carbonizer with the coal feed, some of which accompanies the char feed to the PFB combustor. Ceramic candle filters are operating at 871°C (1,600°F).

6.2.1 PFBC Sensitivity to General Parameters

The capital cost of hot gas particulate filter is about 10 percent the total plant cost of a PFBC plant. As with the IGCC systems, it is possible to vary the capital, consumable, and capacity factor for the base case PFBC, and produce curves that indicate the magnitude of impact on the COE. These effects are shown on Figures 6-4, 6-5, and 6-6. It can be seen that changes in the capital and consumables have less impact on the PFBC COE than on the IGCC, and that capacity factor has a significant impact.

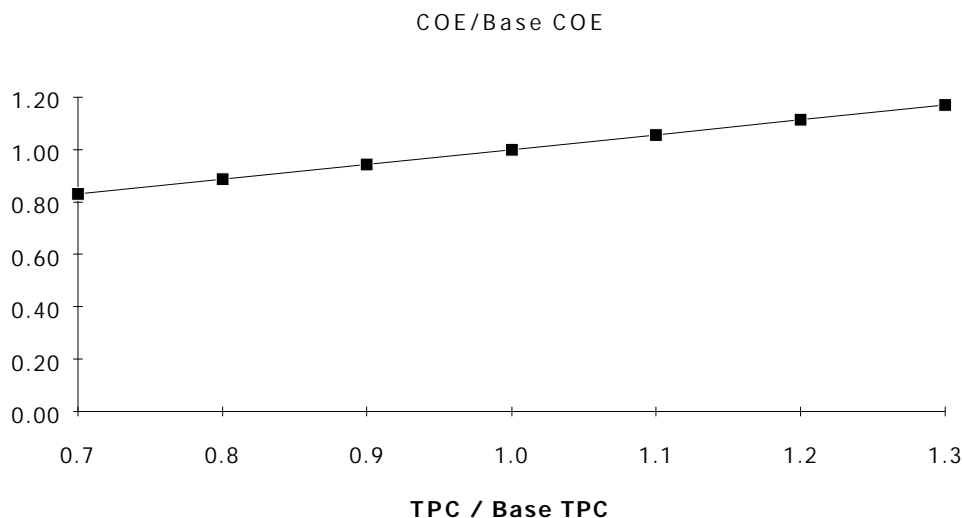


Figure 6-4. PFBC COE Sensitivity to Total Plant Cost

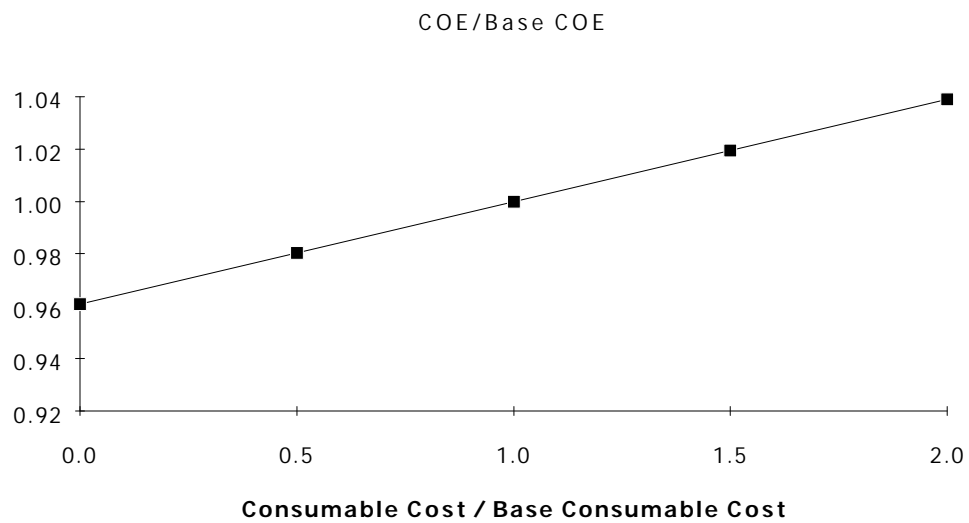


Figure 6-5. PFBC COE Sensitivity to Consumables Cost

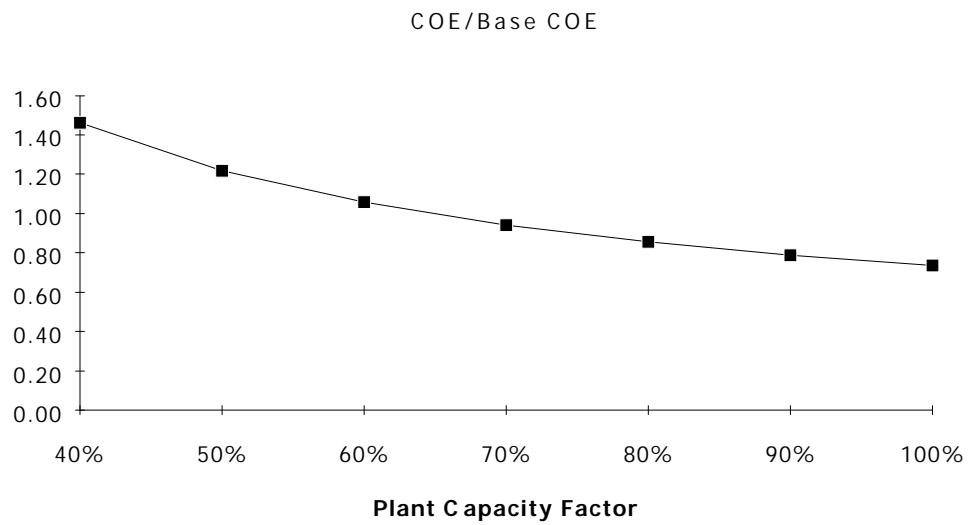


Figure 6-6. PFBC COE Sensitivity to Capacity Factor

6.2.2 PFBC Sensitivity to HGCU Parameters

There are three parameters in filter design/performance that can have economic impacts on the cost and operation of a PFBC particulate collection system: filter face velocity, filter initial cost and filter life. The filter face velocity determines the numbers of candles and vessels that are needed. For the PFBC, which has a large flue gas flow rate, ten vessels are needed. There is less concern for the carbonizer filter. The current price of one candle is about \$500, but attempts are being made to develop less costly candles. Since the PFBC requires a total of nearly 12,000 candles (\$5.9 million) it is clear that a cost reduction can be significant. The same reasoning applies to candle life and replacement costs. Table 6-6 indicates the impact of several design parameters for the carbonizer and PFBC particulate filters on the cost of electricity.

Table 6-6
Impact of Carbonizer Particulate Filters on PFBC COE

Changing parameter	Change to	Carbonizer % Change	PFBC % Change
Face Velocity	2.0 x Base	-1.3%	-3.2%
	0.5 x Base	2.4%	5.7%
Filter Life	5 years	-0.2%	-0.5%
	1 year	1.0%	2.4%
Filter Element Cost	0.7 x Base	-0.3%	-0.7%
	1.3 x Base	0.3%	0.7%
Redundant Trains	1 Redundant	3.0%	7.1%

6.2.3 Findings

Candle filter face velocity controls the number of candles as well as the size and cost of the hot gas cleanup vessel. Also, hot gas filters for larger streams have greater cost impacts than filters for smaller streams. For these two reasons, the candle filter face velocity for the FBC exit stream is the most important gas cleanup parameter influencing the COE of a PFBC plant. Filter element cost and operating life for FBC candle filters are next in importance, although the same percent change in these parameters has only about one-third the impact of face velocity on COE.

The face velocity of the carbonizer filter has less than half the effect on COE as the face velocity of the FBC filter because the carbonizer gas stream is much smaller than the FBC gas stream.

Carbonizer filter element cost and operating life are less important, only 10 or 15 percent as consequential to COE as the face velocity in the FBC filter.

6.3 Lower Temperature Gas Cleanup

Recently there have been second looks within the DOE as to the merit of operating IGCC and PFBC hot gas cleanup systems at the proposed gas temperatures. As indicated in Sections 3.0 and 4.0, the operational issues associated with particulate control and hot gas desulfurization are associated with the severe operating conditions at elevated temperatures, above 850°C (1560°F) for particulates and about 550°C (1000°F) for desulfurization. Several studies have indicated that plant efficiency drop off at lower cleanup temperatures is not as serious as initially anticipated, when viewed from the impact on overall plant cost and cost of electricity.

Although particulate filter research is generally focusing on higher temperature and more severe applications, several studies have indicated the impact on PFBC performance at lower filtration temperatures. Table 6-7 shows the comparative performance impact that resulted from reducing the baseline filtration temperature for PFBC plant designs. The temperature was reduced from the combustor by by-passing a portion of the combustion air, and from the carbonizer by using a syngas cooler.

Table 6-7
Comparative PFBC Performance Impact with HGCU Temperature

Source Reference	Topping Turbine	Turbine Firing Temperature	Baseline HHV Efficiency at 870°C (1600°F)	Reduced Filter Temperature	HHV Efficiency at Reduced Temperature.
White and Others, 1995	W501F	1223°C (2233°F)	46.41%	704°C (1300°F)	44.00%
Parsons Power, 1996	251B12	1149°C (2100°F)	42.6%	760°C (1400°F)	42.6%

The effect of operating a PFBC at reduced temperature serves to transfer the heat from the carbonizer fuel gas and the vitiated PFB air to the steam cycle. The higher the efficiency of the gas turbine relative to the steam turbine, the more impact the reduced temperature will have on plant efficiency. Note that the Parsons 1996 study was for a repowering application utilizing a lower temperature and less efficient gas turbine. This is reflected in the minimal change in plant efficiency with lowered outlet temperatures.

The impact of lower temperature hot gas cleanup on the performance of the baseline plant designs was investigated.

The performance of the baseline IGCC 400 MW_e KRW IGCC plant consisting of the KRW gasifier and the transport reactor hot gas cleanup, zinc titanate sorbent, and the W501G gas turbine in combined cycle was assessed for lower cleanup temperatures. The baseline IGCC hot gas cleanup operates at 604°C (1120°F) and has a HHV efficiency of 46.1 percent. Two variations of the heat and material balances were prepared, with the cleanup temperatures at 482°C (900°F) and 370°C (700°F) respectively. As expected, the efficiency dropped, but the power increased, primarily due to the increased power from the additional steam recovery and higher coal and material throughput to maintain the gas turbine temperature. Table 6-8 summarizes the changes in performance.

Table 6-8
HGPU Impact on IGCC Performance

HGPU Temperature	604°C (1120°F)	482°C (900°F)	370°C (700°F)
Coal, lb/h	251,420	258,528	265,671
Gas Turbine, MWe	239.8	238.8	238.8
Steam Turbine, MWe	176.6	185.2	194.4
Auxiliary Power, MWe	(19.7)	(20.1)	(20.7)
Net Power, MWe	396.7	403.9	411.9
Efficiency, HHV	46.1%	45.7%	45.3%

The significance of this adjustment to the IGCC plant design is that it appears that the year 2000 goals of 45 percent efficiency can still be met with lower temperature HGD. However, the 2010 goal of >50 percent efficiency for an IGCC plant utilizing an advanced turbine system would be achieved more effectively with the higher temperature hot gas cleanup.

The performance of the baseline PFBC plant consisting of the CPFBC boiler with a carbonizer and a W501G combined cycle gas turbine topping cycle was assessed for operation at lower cleanup temperatures. The baseline PFBC plant hot gas cleanup operates at 871°C (1,600°F) and has a HHV efficiency of 48.7 percent. Two variations of the heat and material balances were prepared, with the cleanup temperatures at 790°C (1,450°F) and 704°C (1,300°F) respectively. As expected, the efficiency dropped, but the power increased, primarily due to the additional steam recovery from increased air flow through the CPFBC. Table 6-9 summarizes the changes in performance.

Table 6-9
HGPU Impact on PFBC Performance

HGPU Temperature	871°C (1,600°F)	790°C (1,450°F)	704°C (1,300°F)
Coal, lb/h	258,965	284,953	309,876
Gas Turbine, MW _e	233.9	230.4	226.3
Steam Turbine, MW _e	216.1	244.6	280.1
Auxiliary Power, MW _e	(15.7)	(16.4)	(17.3)
Net Power, MW _e	434.3	458.6	489.1
Efficiency, HHV	48.7%	46.7%	45.8%

As discussed above, the W501G has a higher efficiency than the steam bottoming cycle, and the lowering of exit temperatures produces a more noticeable shift of efficiency toward the purely steam cycle. As with IGCC, it appears that the year 2000 goals of 45 percent efficiency can be met with lower temperature particulate control. However, the 2010 goal of >50 percent efficiency would require higher temperature hot gas cleanup.

6.4 References

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7.0 IMPACT OF HOT GAS CLEANUP SYSTEMS ON PROGRAM GOALS AND TIMEFRAMES

The impact of hot gas cleanup systems on the advanced IGCC and PFBC program goals and timeframes is being assessed to determine their ability to meet, within the next 3 to 5 years, all requirements for future high-temperature turbine operation and environmental acceptability. While initial applications of both these technologies did not utilize hot gas cleanup, hot gas cleanup is necessary to obtain higher system efficiencies, reduce costs, and protect advanced gas turbines from corrosive and erosive impurities.

Commercial cold gas cleanup technology is available for use in IGCC, although this would incur higher costs and an efficiency penalty of approximately two percentage points for air-blown systems. In contrast, advanced PFBC systems are designed to include hot gas filtration since cooling the high-temperature, high-pressure combustion products to low temperatures would negate the efficiency and cost advantages of PFBC.

Thus, hot gas cleanup is a high priority for both the Fossil Energy (FE) coal R&D and the Clean Coal Technology program. To date, neither hot gas desulfurization systems nor the hot gas particulate removal systems have demonstrated the long-term performance requirements for commercial systems.

7.1 Research, Development and Demonstration Goals

Research, development and demonstration (RD&D) efforts in advanced IGCC and PFBC technology are driven by national objectives related to both economic goals and environmental goals. Clean coal technologies will enable the coal-fired plants of the future to produce low-cost electricity with minimal environmental impact, high efficiency, and high reliability.

DOE's coal RD&D power generation program spans the full cycle of technology development. The program consists of research and development, proof of concepts (POC) or process development unit (PDU) tests, and technology demonstration. The R&D programs include fundamental research, filter material and sorbent development, filter and reactor development, modeling and system analysis.

POC or PDU tests are performed to confirm the validity of system concepts, and to provide the data necessary for commercial-scale demonstrations. As technologies mature to this scale, less

promising lines of development are phased out, and private industry assumes a progressively larger share of development costs.

Once a technology passes the POC or PDU stage, an industry partner can be selected via competitive procurement to demonstrate the technology at or near full commercial scale. For these large-scale demonstrations, a significant cost-share, normally 50 percent or greater, is assumed by private industry. Demonstration activities are currently being performed under the DOE CCT Demonstration program for systems that show the greatest potential for fully meeting technical and market requirements.

7.1.1 IGCC Development Goals and Timeframes

Group 1 IGCC plants are now operating and have demonstrated acceptable operability and excellent environmental performance. The plants are characterized by approximately 40 percent efficiency and utilize cold gas cleanup. The DOE CCT program includes three gasification-based power projects, which represent state-of-the-art technology.

A key issue for these technologies is the impact of high capital cost on economic competitiveness. Future improvements to the economics of IGCC are linked mainly to the development of advanced gas turbines with firing temperatures over 1370 °C (2500 °F) and secondarily to development of reliable hot gas cleanup schemes. Hot gas cleanup technology will be tested in two of three CCT demonstration projects. The completion of the CCT projects in the next 3 to 5 years will provide the data and experience for subsequent commercial IGCC plants to be employed beyond the year 2000.

The IGCC program currently has two primary goals:

- To develop an improved IGCC system having a net system efficiency of at least 45 percent, 20 percent lower costs and emissions one-tenth of NSPS by the year 2000.
- To develop an advanced IGCC system with a net system efficiency of at least 50 percent, 25 percent lower costs and emissions one-tenth of NSPS by the year 2010.

It had been expected that hot gas cleanup systems will be necessary to meet both these objectives. With the rapid progress of advanced turbine technology, there is a possibility that hot gas cleanup may not be necessary to reach 45 percent efficiency. However, it will be necessary to meet the 50 percent efficiency goal.

7.1.2 PFBC Development Goals and Timeframes

PFBC technology is in the early stages of commercialization. Five PFBC units of less than 80 MW_e, two in Sweden, one in Spain, one in the United States, and one in Japan, have been placed in operation over the last five years. These PFBC units are all of the bubbling bed variety without hot gas filters and with efficiencies in the 40 percent range. A scale-up of these plants, a 360 MW_e version, has been ordered by Kyushu Electric Power Company in Japan. Startup is scheduled for August 1998.

The DOE CCT demonstration program originally selected two PFBC projects for funding, an 80 MW_e circulating PFBC by Pyropower and a 95 MW_e PFBC by Foster Wheeler. Since the acquisition of Pyropower by Foster Wheeler, both projects were combined into one new project to be built in Lakeland, Florida. The first phase of the new project will be the testing of the Pyropower CPFBC. This will be followed by the installation of a carbonizer and gas turbine at the facility and the testing of an advanced CPFBC. The completion of this project is necessary to provide the data and experience for subsequent commercial PFBC plants.

A fully integrated PFBC system is also scheduled to be tested at the 4 MW_e POC level at the Power Systems Development Facility (PSDF) under construction in Wilsonville, Alabama, sponsored by DOE, Southern Company Services, and EPRI. This PFBC testing will evaluate the integration of all of the components in the PFBC system, with emphasis on the integration of hot gas cleanup ceramic filters and gas turbines. This test facility will provide design input for the planned CCT demonstration unit.

The PFBC program currently has two primary goals:

- To develop and demonstrate PFBCs with emissions one-fifth of NSPS, efficiencies approaching 42 percent, and 20 percent lower costs by 2000.
- To increase the efficiency of PFBC systems to 50 percent, to improve PFBC environmental performance, and to lower cost by 25 percent by 2010.

Hot gas filters were not used on the initial applications of PFBCs. However, hot gas filters are necessary to reach the efficiency goals of advanced PFBC.

7.2 Impact of Hot Gas Particulate Cleanup Systems on Program Goals and Timeframes

The development of devices to remove particulates at high temperature and pressure started for PFBC applications at the conditions of 845 °C (1550 °F) and 1030 kPa (150 psi). These conditions were determined to maximize sulfur removal and the PFBC system efficiency. When hot gas desulfurization of IGCC fuel gases became feasible, the removal of particulates at high temperatures also became necessary for IGCC. The same devices that were used for PFBC were also used in gasification. The IGCC conditions are believed to be less severe: 595 °C (1100 °F) and 2,070-2760 kPa (300-400 psi). The operating pressures for both PFBC and IGCC vary somewhat depending on the technology.

The development of a particulate removal device for gasifiers has advanced to the demonstration plant phase, with vendor confidence of eventual success, even though it started later than for PFBC. Faster development was possible because IGCC operating conditions are less severe than PFBC operating conditions, and because lessons learned from PFBC tests were applied as appropriate. At operating temperatures less than 650 °C (1200 °F), candle filters would be recommended and guaranteed by the filter vendors and the filter system designers. The Piñon Pine IGCC CCT plant, scheduled to start in October 1996, will use Pall Millipore silicon carbide candle filters with conventional clay binders in a Westinghouse filter system. At the same time, slipstream testing will be conducted at the Tampa CCT site on a Pall sintered metal filter. There are still operational issues that must be resolved at both the demonstration and PDU levels; however, these issues should not have an impact on the development schedule of IGCC.

Two commercial size IGCC units are in operation: the Destec Wabash River plant and the Shell plant in Buggenum. Both plants use candle filters for particulate removal but the operating temperatures are low, approximately 260 °C (500 °F). Reports are that the candle filters are operating as expected at Wabash and Buggenum. Although the filter inlet temperatures at these two facilities are low, information and data from these filter systems will be valuable for designing large systems for higher temperature service.

In parallel with the demonstration plant tests, advanced material candle filters and a granular bed filter are scheduled to be tested at the DOE Wilsonville PSDF beginning in late 1996. Other very important tests of four advanced candle filters will continue at the circulating PFBC test facility in Karhula, Finland, which is also a PDU. These advanced filters are operating at 845 °C (1550 °F) without experiencing creep. Filters that are successful at Karhula will receive additional testing at the PSDF.

While there are five PFBC demonstration plants that have operated or are in operation, only two of them have tested particulate removal devices other than cyclones. The Tidd plant tested various candles on a 30 MW_{th} slip stream, and the Wakamatsu plant is currently testing a full-size Asahi tube filter. The Tidd test program produced valuable information on the future design and operation of ceramic barrier filters at PFBC conditions. A filter vessel similar in design to the one used at Tidd was delivered to the Wilsonville test facility to be used for testing candles in the Foster Wheeler Second Generation PFBC PDU. These tests will not start until the PDU is constructed in 1997.

The results of the Wakamatsu demonstration test will not be available until later in 1997, but some tube damage has been reported. If the Wakamatsu test does not prove successful, then demonstration testing must wait for the completion and testing at the CCT demonstration plant. There is a PFBC CCT demonstration plant planned for Lakeland, Florida, where the Westinghouse filter system with candle filters will be utilized. The timeframe for completion of this demonstration plant is the year 2000.

Results of sensitivity studies to determine the impact on COE of filter parameters such as face velocity, filter life, and filter element cost indicated that for IGCC and the PFBC carbonizer there was little impact. For the PFBC, however, the change for a halving of face velocity was a 5.7 percent increase in the COE. This could be significant and emphasizes the importance of face velocity and the accurate determination of this parameter during demonstration testing.

The DOE has a particulate removal development program for accomplishing what is required for the advancement of both high efficiency IGCC and PFBC power systems. The PSDF forms an important part of this program by providing a resource for long-term testing and performance assessment of hot gas particulate removal in IGCC and PFBC system environments. With a PFBC CCT project proceeding, a filter demonstration will be in place by 2000, which will satisfy the program goals for PFBC. Coupled with the long-term testing of advanced candle filters at 845 °C (1550 °F) at Karhula and the PSDF, the hot gas cleanup requirements for future high-temperature turbine operation for PFBC can be met in the next 4 to 6 years. This schedule, however, could be accelerated if commercial size filter vessels are tested with success at the PSDF, or if the tests of the Asahi tube filter at Wakamatsu are successful. For IGCC, the demonstration testing of candles at Piñon Pine will keep the hot gas cleanup development of second generation IGCC within the timeframe of demonstrating all requirements within 3 to 5 years.

7.3 Impact of Hot Gas Desulfurization Systems on Program Goals and Timeframes

Hot gas desulfurization (HGD) program areas focus on the cleanup and fixation of sulfur from synthesis gas for IGCC applications. Areas of concentration for HGD include RD&D on sorbents, processes, and sulfur fixation. HGD RD&D is complemented by hot particulate filtration, which is an integral part of the hot gas cleanup system for IGCC. PFBC sulfur recovery was not considered as an RD&D topic in this assessment. Sulfur removal and fixation from PFBC plants consist of injecting dolomite into the carbonizer and PFB combustor beds to capture greater than 90 percent of the sulfur as CaSO_4 . This is an operational technique, and is not a part of the METC sulfur recovery RD&D program.

The DOE goals for IGCC in 2000 and 2010 provide the guidelines for DOE/FE and METC support of HGD R&D as well as additional support by private industry and institutions. The METC development plan is organized to support the broad spectrum of HGD RD&D, including sorbents, processes, and sulfur fixation.

Emissions requirements of the IGCC plants identified in the DOE goals for 2000 and 2010 can be met utilizing either hot or cold cleanup. Sulfur removal to one-tenth of NSPS can be achieved with state-of-the-art technology using water quench and selective amines or other commercially available processes. Sulfur can also be recovered from a Claus plant followed by a tail gas treatment to minimize SO_2 emissions. The primary reason for utilizing HGD is to achieve the improved efficiency and economics associated with high-temperature gas turbines. Hot gas cleanup is a means of retaining the sensible heat of the high mass flow of fuel gas without the cost and inefficiency associated with recuperative gas-to-gas heat exchangers. The result is a gain of about 2 percentage points in efficiency and reduced capital cost per kilowatt. Additionally, HGD avoids the resultant waste water treatment facilities required by cold cleanup processes.

The IGCC system goals are predicated on having the necessary IGCC components available to achieve the efficiency and cost predictions. The gasifier and gas turbine needed to reach the 2000 goal of 45 percent HHV and 20 percent lower costs are expected to be available. The gasifier, either as an air-blown fluidized bed (KRW) or as an oxygen-blown entrained bed (Destec, Texaco), would be combined with the "H" series turbine (Paul and others, 1996)¹, projected to have above 45 percent HHV IGCC efficiency. However, the 2010 goals of 50 percent HHV efficiency and 25

¹ Paul, T. C., R. W. Schonewald, and P. J. Marolda, "Power Systems for the 21st Century -- "H" Gas turbine Combined Cycles," presented at the Advanced Turbine Systems Annual Program Review, November 7-8, 1996.

percent lower costs are considerably more ambitious, and will require the advanced gas turbine with an economical hot gas cleanup system.

The DOE-supported programs place a high priority on achieving the necessary demonstration of HGD technology in a timely manner. A concerted effort by the DOE and its contractors resulted in the timely availability of both HGD processes and sorbents for demonstration in CCT projects. The Piñon Pine CCT Project is expected to start in March 1997, and will be the most visible milestone for HGD. If successful, the full-scale demonstration will verify performance of the sorbent (Phillip's Z-Sorb III, and others to follow), the process and its operational parameters (Transport Reactor), and the sulfator. Similarly, the demonstration of the GE moving bed process in a slip stream at Tampa Electric Company CCT Project will, if successful, demonstrate HGD integration with a sulfuric acid plant. Technology demonstrations are in place for HGD combined with hot gas filtration.

Although the HGD technology may be demonstrated to "work," the cost of the sorbent may continue to be a significant factor in the economic viability of IGCC. The assessment has shown that the sorbent unit cost and attrition rate have the largest impacts on the cost of electricity for the IGCC plants reviewed. The DOE continues to support sorbent development having the objectives of increased attrition resistance and retention of sulfur capacity. These parameters have also been identified during testing as being significant, so improved attrition and sorbent capacity are primary objectives of sorbent development. As development progresses, the potential commercialization of HGD is influencing research to focus on additional features that can be patented, such as low temperature regeneration light-off.

7.4 Impact of Trace Contaminant Removal Systems on Program Goals and Timeframes

This program area focuses on developing gas cleanup subsystems that will be used by advanced power systems to control trace contaminants, such as HAPs, alkali metals, chlorides, and ammonia. Trace contaminants in IGCC and PFBC power systems may require control for either process reasons or to ensure that environmental standards are met.

HAPs research to date has been aimed at defining an emission database and documenting the effectiveness of present control technologies on reducing HAP emissions. Preliminary results from testing programs for advanced power systems indicate that the emissions are extremely low for most metals.

Mercury is the only HAP likely to be controlled. The EPA interim report to Congress with its recommendations for control measures was due to be issued on April 15, 1996 but has been delayed. A tentative schedule calls for proposed regulations no later than December 15, 1998 and promulgated regulations by December 15, 2000, with a phase-in period to follow. Technologies to control mercury emissions may well be needed in the near future for all coal-fired power plants. The control of mercury through the injection of carbon-based material has been demonstrated, but a number of technical issues still need to be addressed before the technology can be implemented.

Fixed bed alkali getters will be tested on both fluid streams of the Advanced Pressurized Fluidized Bed Combustion module of the Power System Development Facility after construction is completed in 1997. Also, a granular bed filter will be tested on the Transport Reactor module in 1997. After evaluation for particulate control, the opportunity exists to evaluate the filter with a reactive medium for the control of sulfur and alkali compounds. These proof-of-concept tests will determine both the magnitude of the emissions and the ability of the getters to reduce alkali vapor levels. Several sources have indicated that alkali vapors could react with ceramic candle filter media. A major concern is alkali attack of the binders. Long-term testing is necessary to define the extent of this issue.

The primary concerns for IGCC and PFBC power plants from chloride contaminants are the formation of chloride compounds and, if they build up in recycle loops such as in the GE desulfurization process, their subsequent deposits on syngas coolers and heat exchangers. Several programs are in place to evaluate chloride control technology. Slip stream tests on the GE Hot Gas Cleanup facility at the Tampa Electric CCT demonstration were planned for 1996. These proof-of-concept tests will provide design input for chloride control, if necessary, in future demonstration plants.

A portion of the fuel-bound nitrogen is converted during gasification into NH_3 and trace quantities of HCN . Some of the NH_3 is subject to conversion to NO_x in the downstream gas turbine so that ammonia removal may be necessary to meet more stringent NO_x emission limits or for certain gasifiers that produce higher levels of NH_3 . The approaches to NH_3 removal which are being developed involved rich-quench-lean (RQL) combustion and catalytic decomposition. RQL combustion techniques are being developed to meet present NO_x emission limits for fuels which contain fuel bound nitrogen. Laboratory work has been continuing on the catalytic decomposition of NH_3 . Plans are to continue work to develop innovative and effective techniques for removal of ammonia in coal gas.

Trace contaminant control would have little impact on the performance or efficiency of IGCC or PFBC power plants. The pressure drops and temperature losses would be small and would have little impact on the overall system performance or efficiency. Except for mercury, trace contaminant control should have small impact on costs. Controls for mercury would impose additional costs, which could be significant.

Trace contaminant control should not impact the developmental timeframe of these technologies. The PDU and slipstream testing of alkali and chloride removal technologies will provide, in a timely fashion, design input for future demonstration plants. Indications are that alkali vapors could react with the ceramic candle filter media. Most of the work with alkali getters including the PDU tests has been done downstream of the particulate filter. Additional work may be needed to develop techniques for upstream alkali removal.

The laboratory development of ammonia decomposition continues, and the technology can be phased in as the development warrants or the NO_x limits make necessary. The development of mercury control technology is just beginning, and many critical issues need to be resolved before the technology can be implemented. However, this technology should not impact the developmental timeframe of IGCC and PFBC since a relatively long phase in period is planned for mercury control technology.

8.0 FINDINGS AND CONCLUSIONS

To comply with the NRC recommendation that an assessment of hot gas cleanup systems be undertaken, the Office of Coal Conversion/Fossil Energy asked Parsons Power Group Inc. to perform a comprehensive assessment of hot gas cleanup systems under Task 18 of U.S.DOE/FE Contract DE-AC01-94FE62647. Detailed information on the status of development, impact on cost and performance, technical issues, and need for further development for each system can be found throughout this report. The major findings and conclusions were:

1. The major benefit from hot gas cleanup is seen in higher system efficiencies resulting from retention and utilization of the sensible heat in product gases. Several development programs for hot gas desulfurization systems and hot gas particulate removal systems are under way, as well as control of other pertinent contaminants such as alkali metals and chlorides. Results to date have verified the technical ability to clean hot gases, and longer duration tests will establish the long-term durability record required for commercial acceptance.
2. A coordinated program is in place for the development of hot gas cleanup systems and to resolve critical issues. A development plan is being implemented through the demonstration phase for hot gas particulate removal systems, desulfurization systems, and trace contaminant removal systems. This program consists of research and development, proof-of-concept tests, and technology demonstrations.
3. Successful completion of these development plans will demonstrate the ability to meet, within the next 3 to 5 years for IGCC and 4 to 6 years for PFBC, all requirements for future high-temperature turbine operation and environmental acceptability.
4. Key tests planned for 1996 and 1997 are critical to the demonstration of both IGCC and PFBC cleanup systems. PFBC tests include filter tests at Karhula, Finland; at the Wilsonville, Alabama PSDF; and at the Wakamatsu PFBC demonstration plant in Japan. IGCC tests include filter tests at the PSDF, slipstream tests of a filter and desulfurization system at the Tampa Electric Company CCT project, and a hot gas cleanup demonstration at the Piñon Pine CCT project.
5. Hot gas cleanup systems costs are on the order of 10 to 15 percent of the total plant capital cost for IGCC and 10 percent for PFBC. While significant, this is a much smaller portion than for any other major system. The most critical parameters impacting the cost of electricity include the face velocity for particulate control system, and sorbent attrition and sorbent cost for the desulfurization system.

6. The rapid progress in the development of advanced gas turbines coupled with the successful development of reliable hot gas cleanup systems will assure that the IGCC and PFBC program goals are achieved in the proposed timeframe.

Table 1-1 Advanced Coal-Based IGCC and PFBC Power Systems

Technology	Design Efficiency (percent)	Coal Conversion Components	Power Generation Components	Particulate Control System	SO ₂ Control System	NO _x Control System
Pulverized Coal	38-42	Supercritical boiler	3500 psi steam turbine	ESP or Fabric Filter	Wet lime or limestone FGD	Low NO _x burners or SCR
<u>Group 1 Systems</u>						
PFBC	~40	Bubbling and circulating bed PFBC units	1600 °F gas turbine + 2400 psi steam turbine	Cyclones and post turbine ESP or fabric bag filter	In-bed dolomite	Combustion controls
IGCC	~40	Oxygen-blown entrained bed gasifiers	2350 °F gas turbine + steam turbine	Cold gas quenching	Cold gas H ₂ S absorption	Cold gas cleanup + steam injection
<u>Group 2 Systems</u>						
PFBC	45	Coal pyrolyzer + circulating PFBC	2350 °F gas turbine + 2400 psi steam turbine	Hot gas filtration	In-bed dolomite	Combustion controls
IGCC	45	Oxygen- or air-blown fluidized bed gasifier	2350 °F or 2500+ °F gas turbine + steam turbine	Hot gas filtration	Hot gas desulfurization + in-bed limestone (optional)	Combustion controls

Table 1-1 Advanced Coal-Based IGCC and PFBC Power Systems (Continued)

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